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Essays on Aggregate Performance and Competition

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Abstract

This thesis examines various forces that affect aggregate performance. In particular, it focuses on competitive pressures and analyses their determinants. It also analyses the importance of the human capital portfolio composition for aggregate performance. Specifically, in the first chapter, it offers an endogenous growth framework, where it models knowledge (patent) licensing among high-tech firms. In such a framework it evaluates how different types of competitive pressure can matter for innovation in high-tech industries. In the second chapter, it offers empirical evidence that the country-wide uptake of telecommunication technologies increases competition in services and goods markets. In turn, in the third chapter, it defines two types of human capital and suggests how the human capital portfolio matters for long-run growth and welfare.

In the first chapter, I present an endogenous growth model, where the engine of growth is in-house R&D performed by high-tech firms. I model knowledge (patent) licensing among high-tech firms where licenses are essentially permits for licensees to use the knowledge of the licensor in the R&D process. I show that if there is knowledge licensing, high-tech firms innovate more, and economic growth is higher than when there are knowledge spillovers, or there is no exchange of knowledge among high-tech firms. Conditionally that high-tech firms innovate, I show that increasing intensity and toughness of competition in the high-tech industry increases innovation. When there is an exchange of knowledge among high-tech firms, in terms of licensing or spillovers, increasing the number of high-tech firms also increases innovation. However, when there is no exchange of knowledge, the relationship between innovation in the high-tech industry and the number of high-tech firms has an inverted-U shape.

Finally, endogenizing the number of high-tech firms I show again that when there is knowledge licensing, high-tech firms innovate more and economic growth is higher than in the latter two cases. However, the number of high-tech firms is lower.

In the second chapter, co-authored with Anna Kochanova, we use evidence from 21 EU countries to investigate the relationship between the country-wide uptake of high-tech goods such as telecommunications and the level of product market competition in services and goods markets. We find that the uptake of telecommunication technologies significantly increases the level of product market competition. Our result is consistent with the view that the use of these technologies can lower the costs of firm entry. This result contributes to the ongoing debate about the impact of telecommunication technologies, as well as information and communication technologies on aggregate performance. In particular, since competitive pressures matter for allocative and productive efficiency, our results imply that the benefits from a particular type of ICT, telecommunication technologies, may come not only from direct use (e.g., email

vs. mail) but also from higher competition.

In the third chapter, co-authored with Evangelia Vourvachaki and Sergey Slobodyan, we propose a new way to differentiate horizontally across skill types in order to analyze the impact of human capital composition on aggregate economic performance. As in the existing literature, we exploit the cross-occupational differences with an exception that our definition derives from cross-industry heterogeneity in the production function: We differentiate human capital skills according to their "industry specificity." In particular, we define two types of human capital: "specific" and "general." As specific human capital, we define a set of skills that are required for production in few industries. As general human capital, we define a set of skills that are required for production in a broad set of industries.

We use Czech labor survey data to summarize the facts regarding the employment and education levels of the two types of human capital for the Czech economy. We find a rather uniform level of skills across the specific and general types of human capital that agrees with our horizontal differentiation of skills. Moreover, we find that in 2007 approximately 36 percent of total labor input was comprised of specific human capital. Our evidence also suggests that this share has been steadily falling since the mid-90s.

To provide an explanation for this trend and illustrate how it can matter for long-run growth and welfare, we build up an endogenous growth model, where education and R&D are costly activities. In the model, both general and specific human capital are used in final goods production, while only specific human capital can serve as input into the educational sector and R&D. We also explicitly take into account the complementarity between basic R&D and the education process and positive externalities in R&D. In this respect, the model implies a positive relation between specific human capital intensity and economic growth. This suggests that there can be long-run welfare costs involved in the falling share of specific human capital as observed in the Czech data. We also discuss optimal educational policies in the presence of market distortions.

Abstrakt

Tato disertační práce zkoumá různé síly, které ovlivňují agregátní výkonnost. Zejména se zaměřuje na konkurenční tlaky a analyzuje jejich determinanty. Práce také analyzuje důležitost složení portfolia lidského kapitálu pro agregátní výkonnost. Konkrétně v první kapitole představuje rámec endogenního růstu, ve kterém modeluje licencování znalostí (patentů) mezi high-tech firmami. V tomto rámci pak vyhodnocuje, jak rozdílné druhy konkurenčních tlaků mohou být důležité pro inovace v high-tech odvětví. V druhé kapitole představuje empirické důkazy o tom, že široké přijetí telekomunikačních technologií v určité zemi vede ke zvýšení konkurence na trhu zboží a služeb. Pro změnu ve třetí kapitole definuje dva typy lidského kapitálu a ukazuje, jak je portfolio lidského kapitálu důležité pro dlouhodobý růst a prosperitu.

V první kapitole představuji model endogenního růstu, kde zdrojem růstu je výzkum a vývoj high-tech firem. Modeluji licencování znalostí (patentů) mezi high-tech firmami, kdy licence v zásadě umožňují jejímu držiteli využívat znalosti prodejce licence. Ukazuji, že pokud existuje licencování znalostí, high-tech podniky více inovují a ekonomický růst je vyšší než v případech, kdy existuje přelévání znalostí nebo nedochází k výměně znalostí mezi high-tech firmami. V případech, kdy high-tech firmy inovují, ukazuji, že vyšší intenzita a tvrdost konkurence v high-tech odvětví zvyšuje inovace. V případech, kdy dochází k výměně znalostí mezi high-tech firmami v podobě licencování nebo přelévání, zvyšování počtu high-tech firem také zvyšuje inovace. Avšak v případě, kdy nedochází k výměně znalostí, závislost mezi inovacemi v high-tech odvětví a množstvím firem má tvar otočeného U.

Konečně v případě, že počet firem je endogenní, ukazuji znovu, že při existenci licencování znalostí high-tech firmy inovují více a ekonomický růst je vyšší než ve zbývajících dvou případech. Množství firem je ale menší.

V druhé kapitole, jejíž spoluautorkou je Anna Kochanova, používáme data z 21 zemí EU ke zkoumání vztahu mezi širokým přijetím high-tech zboží jako jsou telekomunikace a úrovní konkurence na trhu zboží a služeb. Zjišťujeme, že přijetí telekomunikačních technologií signifikantně zvyšuje úroveň konkurence na trhu produktů. Naše výsledky jsou konzistentní s názorem, že používání těchto technologií snižuje vstupní náklady firem. Tento výsledek přispívá k probíhající debatě o dopadu telekomunikačních technologií i informačních a komunikačních technologií (ICT) na agregátní výkonnost. Konkrétně pak, vzhledem k tomu, že konkurenční tlaky jsou důležité pro alokační a produkční efektivitu, naše výsledky implikují, že výhody z konkrétního typu ICT, telekomunikačních technologií, mohou plynout nejen z přímého používání (např.

email versus pošta), ale také z vyšší konkurence.

Ve třetí kapitole, jejíž spoluautory jsou Evangelia Vourvachaki a Sergey Slobodyan, navrhujeme nový způsob, jak diferencovat mezi typy dovedností, abychom mohli analyzovat dopad složení lidského kapitálu na agregátní ekonomickou výkonnost. Podobně jako v existující literatuře využíváme rozdíly mezi zaměstnáními s tím rozdílem, že naše definice vychází z různorodosti produkční funkce mezi odvětvími: Rozlišujeme dovednosti v rámci lidského kapitálu podle jejich „odvětvové specifičnosti". Konkrétně definujeme dva typy lidského kapitálu „specifický" a „obecný". Jako specifický lidský kapitál definujeme soubor dovedností, které jsou potřebné pro produkci v omezeném počtu odvětví. Zatímco obecný lidský kapitál definujeme jako soubor dovedností, které jsou požadovány pro produkci ve velké množině odvětví.

Používáme data z průzkumů na českém trhu práce ke shrnutí faktů týkajících se zaměstnanosti a úrovně vzdělání dvou typů lidského kapitálu pro českou ekonomiku. Zjišťujeme spíše rovnoměrné rozdělení úrovně dovedností mezi specifický a obecný typ lidského kapitálu, což se shoduje s naším horizontální rozdělením dovedností. Dále zjišťujeme, že v roce 2007 přibližně 36 procent celkového pracovního vstupu zahrnoval specifický lidský kapitál. Naše výsledky také naznačují, že tento podíl setrvale klesal od poloviny 90. let.

Abychom poskytli vysvětlení tohoto trendu a ilustrovali, jaké může mít důsledky pro dlouhodobý růst a prosperity, konstruujeme model endogenního růstu, ve kterém vzdělání a výzkum a vývoj jsou nákladné aktivity. V modelu je obecný i specifický lidský kapitál použit k produkci finálních statků, zatímco pouze specifický kapitál může být použit jako vstup do sektoru vzdělání a výzkumu a vývoje. Také explicitně bereme v potaz komplementaritu mezi základním výzkumem a vývojem a procesem vzdělávání a pozitivní externality při výzkumu a vývoji. V tomto ohledu model implikuje pozitivní závislost mezi intenzitou specifického lidského kapitálu a ekonomickým růstem. Toto by znamenalo, že klesající podíl specifického lidského kapitálu, pozorovaný na českých datech, může představovat dlouhodobé negativní dopady na prosperitu. Také diskutujeme optimální politiku vzdělanosti za přítomnosti deformace trhů.

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Chapter 1

Knowledge Licensing in a Model of R&D-driven Endogenous Growth

Abstract

In this paper, I present an endogenous growth model where the engine of growth is in-house R&D performed by high-tech firms. I model knowledge (patent) licensing among high-tech firms. I show that if there is knowledge licensing, high-tech firms innovate more and economic growth is higher than in cases when there are knowledge spillovers or there is no exchange of knowledge among high-tech firms. However, when there is knowledge licensing, the number of high-tech firms is lower than when there are knowledge spillovers or there is no exchange of knowledge.

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1.1 Introduction

A number of growth models treat private firms' intentional investments in R&D as the driver of long-run growth and welfare (e.g., Romer, 1990; Aghion and Howitt, 1992; Smulders and van de Klundert, 1995). These models assume that there are knowledge spillovers in the R&D process, and R&D builds on a pool of knowledge. In this sense, these growth models abstract from the role of knowledge (patent) licensing and from the details about the exchange of knowledge in the economy. Nevertheless, licensing and establishing consortia for exchanging patents is common in high-tech industries (e.g., Hagedoorn, 1993, 2002).[2] Moreover, it has been extensively argued that exchanging patents plays a significant role for innovation in these industries (e.g., Grindley and Teece, 1997; Shapiro, 2001; Clark, Piccolo, Stanton, and Tyson, 2000).[3] For instance, yet at the beginning of the previous century, the major players in the Radio, Television, and Communication Equipment industry in the United States experienced difficulties in innovating and advancing their products until the establishment of a patent consortium, RCA Corporation. Meanwhile, high-tech industries are the top private R&D performers, and there is a large body of anecdotal and rigorous empirical evidence which show that they make a significant contribution to economic growth (e.g., Helpman, 1998; Jorgenson, Ho, and Stiroh, 2005).

In this paper, I present an endogenous growth model, where high-tech firms engage in intra-firm (or in-house) R&D and that drives long-run growth. High-tech firms have exclusive rights to the type of their product. In a high-tech firm, the innovation enhances firm/product-specific knowledge, which reduces the firm's marginal costs or increases the quality of its product. High-tech firms finance their R&D expenditures from operating profits. They set prices and compete strategically in their output market. My point of departure is that I model knowledge (patent) licensing among high-tech firms. The knowledge generated in a high-tech firm cannot be used for free, but it can be licensed. Given that each high-tech firm produces a distinct type of good, for a high-tech firm the knowledge of other high-tech firms is complementary to its own. If a high-tech firm licenses the knowledge of another, it can combine that knowledge with its own and improve its in-house R&D process since the latter builds on the knowledge that the firm possesses.

In such a setup, I show how market concentration, intensity of competition as

[2] In terms of the 2-digit ISIC (Rev. 3), according to OECD STAN data, high-tech industries as measured by R&D intensity are, for example, 24, 29, 30, 31, 32, 33, 34, 35, 64 and 72.

[3] Currently, there are virtually no comprehensive data for measuring the size of the market for patents and other types of intellectual property. According to some estimates (Robbins, 2009) in the US in 2002 corporate domestic income from licensing patents and trade secrets was $50 billion or approximately 25 percent of total private R&D expenditure. Moreover, it was expected to grow at more than a 10 percent annual rate.

measured by the elasticity of substitution between high-tech goods, and type of competition (Cournot or Bertrand) can matter for innovation in high-tech industry and aggregate performance. I contrast the inference from this setup to the inference from setups where there is no exchange of knowledge among high-tech firms and/or there are knowledge spillovers (i.e., firms obtain the knowledge of others for free). Further, it is often conjectured that the use of high-tech goods such as phones and PCs entails positive externalities, which lower the transaction costs and increase the efficiency of users (e.g., Leff, 1984). I assess how innovation in the high-tech industry and aggregate performance depend on the magnitude of such externalities.

I show that high-tech firms innovate more and the economy grows at a higher rate in case when there is knowledge licensing among high-tech firms than when there are knowledge spillovers. This result holds since when there is knowledge licensing, high-tech firms better appropriate the benefits from their R&D. The availability of complementary knowledge also motivates innovation in high-tech industry. High-tech firms innovate more and the economy grows at a higher rate when there is an exchange of knowledge among high-tech firms than when there is no exchange. This is because R&D builds on a bigger pool of knowledge in case when there is an exchange of knowledge. Moreover, when there is no knowledge exchange, high-tech firms might not innovate at all if there are many of them in the market. The driver behind this result is the scarcity of R&D inputs available per high-tech firm if there are many such firms.

When there is an exchange of knowledge among high-tech firms in the form of licensing or spillovers, innovation in the industry and economic growth increase with the number of high-tech firms as long as these firms have sufficient incentives to innovate. The driver behind this result is the relative price distortions, which are due to price setting by high-tech firms. This distortion adversely affects the demand for high-tech goods. Given that high-tech firms interact strategically in the output market, a higher number of firms implies lower mark-ups and a lower distortion. This increases the demand for high-tech goods and implies higher output and investments in R&D in the high-tech industry.[4] However, if there is no exchange of knowledge among high-tech firms, then increasing the number of firms has two effects on innovation. One is the lower distortion, which is positive. The other is negative and is due to the lower amount of R&D inputs available per firm. When the number of high-tech firms is relatively low, the positive effect dominates, whereas for a relatively high number of firms, the negative effect dominates. When there is knowledge exchange among high-tech firms, this negative effect is offset by more complementary knowledge made available by the

[4] O'Donoghue and Zweimüller (2004) have a similar result in a Schumpeterian growth model. Vives (2008) shows that such a result can also hold in partial equilibrium for various types of demand functions.

firms.

I further show that in all the setups I consider, high-tech industry innovation and economic growth increase with the intensity of competition, again, provided that high-tech firms have sufficient incentives to innovate. Under such a condition, tougher competition, which is defined as a type of competition with lower mark-ups (Bertrand vs. Cournot; Sutton, 1991), also implies more innovation and higher growth. These results are in line with the results of Smulders and van de Klundert (1995) and van de Klundert and Smulders (1997) and hold because both more intensive and tougher competition reduce mark-ups and relative price distortions.[5]

The higher magnitude of positive externalities from the use of high-tech goods implies lower innovation in the high-tech industry. Nevertheless, economic growth increases with the magnitude of these externalities. Innovation declines because the higher magnitude of positive externalities brings no additional internalized benefit to high-tech firms, and in equilibrium, it implies a higher rate of interest. In turn, economic growth increases since the higher magnitude of externalities implies a higher contribution of innovation from the industry to growth.

Finally, I endogenize the number of high-tech firms assuming a cost-free entry. High-tech industry innovation and economic growth are the lowest when there is no exchange of knowledge among these firms. In turn, innovation and economic growth are the highest when there is knowledge licensing among these firms. This happens, however, at the expense of the number of high-tech firms (or of the variety of high-tech goods.) In other words, the number of high-tech firms is the lowest when there is knowledge licensing and the highest when there is no exchange of knowledge.

Increasing the intensity and/or toughness of competition reduces the number of firms. When there is an exchange of knowledge among high-tech firms, this has no effect, however, on allocations, innovation, and economic growth. Meanwhile, allocations change, and innovation and economic growth tend to increase with the intensity and toughness of competition when there is no exchange of knowledge among high-tech firms.

This paper is related to the endogenous growth literature (e.g., Romer, 1990; Aghion and Howitt, 1992; Smulders and van de Klundert, 1995), where the positive growth of the economy on a balanced growth path is a result of technological and preference factors. In particular, it is related to studies which in an endogenous growth framework suggest how the aggregate performance can be affected by imperfect competition in an industry where the firms engage in in-house R&D (e.g., van de Klundert and Smulders, 1997). It contributes to these streams of studies while showing how knowledge licensing

[5]The results regarding the relation between innovation and different types of competitive pressure are consistent with the empirical findings of Nickell (1996), Blundell, Griffith, and van Reenen (1999), and Aghion, Bloom, Blundell, Griffith, and Howitt (2005).

in such an industry can affect innovation and aggregate performance. It also contributes by showing how positive externalities from the use of goods from such an industry can affect the decentralized equilibrium outcomes.

Further, there is a number of papers that model knowledge (patent) and technology licensing in the standard Schumpeterian growth framework and show how patent policy and international technology licensing can affect innovation and growth (e.g., O'Donoghue and Zweimüller, 2004; Yang and Maskus, 2001; Tanaka, Iwaisako, and Futagami, 2007). In these papers, licensing happens between incumbents and entrants given that in the standard Schumpeterian growth framework, incumbents have no incentives to innovate. Licensing does not explicitly aid R&D processes, and licenses are essentially permits for production. In such a framework in order to maintain incentives for licensing, these papers assume that either licensors and licensees (incumbents and entrants) collude in the product market, or licensees can access a larger market (e.g., one of the countries bans FDI). The share in collective profits and licensing fees compensate the incumbents' loss of the product market (and costs of technology transfer) and are either exogenous or exogenously determined by patent policy. In contrast, this paper has a non-tournament framework where incumbents innovate because that allows for stealing a market share, and licensing happens among incumbents. Firms have the incentive to license knowledge from other firms because that aids their R&D process. Further, license fees are determined by the structure of the market for knowledge, which can depend on patent policy and supply and demand conditions. To that end, the framework and analysis of this paper can be thought to be complementary.

In this paper, the value of the knowledge/patent of a firm is the sum of license fees that the firm collects and its benefit from using the knowledge in the production of its good and in R&D. This is the Lindahl value of the knowledge although in this context, knowledge is not a purely public good since it is excludable. To that extent, this paper is related to a number of others that derive the Lindahl price of knowledge in an R&D-driven growth framework (e.g., Grimaud and Tournemaine, 2006; Chantrel, Grimaud, and Tournemaine, 2012). Methodologically, the work here is most closely related to Chantrel et al. (2012). Given their focus, the authors in a similar growth framework model firms that do not have their own knowledge and need to purchase it for production and R&D from the "public domain." Moreover, firms engage in in-house R&D in order to sell their R&D output in the "public domain." These proceeds are the sole motives for performing R&D.

There is also a large body of firm- and industry-level studies that analyzes the implications of patent licensing, patent consortia or pools, and knowledge exchange among firms on innovation and market conduct (e.g., Gallini, 1984; Gallini and Winter, 1985; Shapiro, 1985; Katz and Shapiro, 1985; Bessen and Maskin, 2009). This paper analyzes such issues at the aggregate level in a dynamic general equilibrium framework, which assumes an undistorted market for knowledge/patents. This assumption allows it to have a tractable inference and can be justified to the extent that this paper aims to address long-run issues, for example. In turn, the dynamic general equilibrium framework allows it to endogenize the growth rate of the economy and the effect of knowledge licensing on, for example, interest rates, which affect the incentives to perform R&D. Licensing in this paper *ceteris paribus* motivates R&D. This, in turn, implies a higher growth rate and a higher rate of interest, which reduces the incentives to perform R&D.

The next section offers the model. Section 3 analyzes the features of a dynamic equilibrium, and section 4 concludes.

1.2 The Model

Households

The economy is populated by a continuum of identical and infinitely lived households of mass one. The representative household is endowed with a fixed amount of labor (L). It inelastically supplies its labor to firms that produce final goods and to high-tech firms. The household has a standard CIES utility function with an inter-temporal substitution parameter $\frac{1}{\theta}$ and discounts the future streams of utility with rate ρ $(\theta, \rho > 0)$. The utility gains are from the consumption of amount C of final goods. The lifetime utility of the household is

$$U = \int_0^{+\infty} \frac{C_t^{1-\theta} - 1}{1-\theta} \exp\left(-\rho t\right) dt. \tag{1.1}$$

The household maximizes its lifetime utility subject to a budget constraint,

$$\dot{A} = rA + wL - C, \tag{1.2}$$

where A are the household's asset holdings $[A\left(0\right) > 0]$, r and w are the market returns on its asset holdings and labor supply.

The optimal rule that follows from the household's optimal problem is the standard Euler equation,

$$\frac{\dot{C}}{C} = \frac{1}{\theta}\left(r - \rho\right). \tag{1.3}$$

This, together with budget constraint (1.2), describes the paths of the household's consumption and assets.

Final Goods

Final goods are homogeneous, Y. The household's demand for final goods is served by a representative producer. The production of final goods requires labor and X, which is a Dixit-Stiglitz composite of high-tech goods $\{x_i\}_{i=1}^N$ with an elasticity of substitution ε.

Ceteris paribus the increasing demand of X creates externalities in final goods production, which are measured by $\tilde{X}$. These externalities increase the productivity of the final goods producers. For example, these externalities stand for network effects that stem from using high-tech goods such as PCs and phones.

The production of the final goods has a Cobb-Douglas technology and is given by

$$Y = \tilde{X} X^{\sigma} L_Y^{1-\sigma}, \tag{1.4}$$

$$X = \left(\sum_{i=1}^{N} x_i^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}}, \tag{1.5}$$

$$1 > \sigma > 0, \varepsilon > 1,$$

where L_Y is the share of the labor force employed in final goods production.

The representative producer solves the following problem.

$$\max_{L_Y, X} \left\{ Y - wL_Y - \sum_{i=1}^{N} p_{x_i} x_i \right\}$$
$$s.t.$$
$$(3.1),$$

where Y is the numeraire. The optimal rules that follow from this problem describe the final goods producer's demand for labor and for high-tech goods.

$$[L_Y] : wL_Y = (1-\sigma) Y, \tag{1.6}$$

$$[x_j] : x_j = X \left(\frac{P_X}{p_{x_j}} \right)^{\varepsilon} \text{ for } \forall j = 1, ..., N, \tag{1.7}$$

where P_X is an index of p_x

$$P_X = \left(\sum_{i=1}^{N} p_{x_i}^{1-\varepsilon} \right)^{\frac{1}{1-\varepsilon}}. \tag{1.8}$$

By construction this index is the private marginal value of X. Moreover, given that X is constant returns to scale in high-tech goods, the following two conditions hold.

$$P_X X = \sigma Y, \tag{1.9}$$

$$P_X X = \sum_{i=1}^{N} p_{x_i} x_i. \tag{1.10}$$

Further, I assume that the measure of externalities $\tilde{X}$ is given by

$$\tilde{X} = X^{\mu},$$

where μ measures the strength of these externalities $(1 - \sigma > \mu \geq 0)$.[6]

High-tech Goods

At any time t, there are $N(t)$ producers in the high-tech industry.[7]

Production

Each high-tech firm owns a design (blueprint) of a distinct high-tech good x, which it produces. The production of a high-tech good requires labor input L_x. The production function of a high-tech good x is

$$x = \lambda L_x, \tag{1.11}$$

where λ measures the producer's knowledge of the production process or quality of the high-tech good. This knowledge is firm/product-specific since each high-tech firm produces a distinct good.

High-tech firms are price setters in their output market and discount their future profit streams π with the market interest rate r. I assume that high-tech firms cannot collude in the output market.

Knowledge Accumulation

High-tech firms can engage in R&D for accumulating knowledge and increasing λ. This can be interpreted as a process innovation that increases productivity (the firms are able to produce more of x) or as a quality upgrade (the firms are able to produce the same amount of higher quality x). Knowledge is non-rival so that potentially it can be used at the same time in multiple places/firms.

In this section, I offer three different settings of knowledge accumulation/the R&D process. The differences stem from whether and how knowledge is exchanged among high-tech firms.[8,9]

[6] It is necessary to have $1-\sigma > \mu$ in order for the production function of final goods (3.1) to be concave in X in the Social Planner's problem.

[7] In order to avoid complications arising from integer constraints I allow N to be a real number.

[8] The functional forms of the knowledge accumulation processes are selected so that they ensure a balanced growth path.

[9] In these setups, each high-tech firm engages in in-house R&D, and there is no R&D cooperation.

Hereafter, when appropriate for ease of exposition, I describe the properties of the high-tech industry while taking as an example high-tech firm j, $j \in (1, N]$. In order to improve its knowledge λ_j the firm needs to hire researchers/labor L_{r_j}. Researchers use the current knowledge of the firm in order to create better knowledge.

Knowledge Licensing: This is the benchmark setup (S.1). Knowledge in this setup can be licensed. In the market for knowledge the licensors (or the suppliers of knowledge) have bargaining power in the sense that they can make a 'take it or leave it' offer. I assume that license contracts do not allow sub-licensing.

The benefit from licensing knowledge is that it can be used in the in-house R&D process. If high-tech firm j decides to license knowledge from other high-tech firms, its researchers combine that knowledge with the knowledge available in the firm in order to produce new knowledge. The knowledge available in the firm is an essential input in the knowledge accumulation process of the firm. Moreover, it is the only essential input. This implies that the high-tech firm does not need to acquire knowledge from other firms in order to advance its own. However, it needs to have its knowledge for building on it. This is in line with the notion that high-tech firms produce distinct goods.

The knowledge accumulation/R&D process is given by

$$\dot{\lambda}_j = \xi \left[\sum_{i=1}^{N} (u_{i,j}\lambda_i)^{\alpha} \right] \lambda_j^{1-\alpha} L_{r_j}, \qquad (1.12)$$
$$\xi > 0, 1 > \alpha > 0,$$

where ξ is an exogenous efficiency level, $u_{i,j}$ is the share of knowledge of firm i (λ_i) that firm j licenses, and $u_{j,j} \equiv 1$.[10]

It can be shown that in (1.12) the elasticity of substitution between the different types of knowledge that the high-tech firm licenses is equal to $\frac{1}{1-\alpha}$. It can also be shown that the elasticity of substitution between the high-tech firm's knowledge and any knowledge that it licenses is lower than $\frac{1}{1-\alpha}$ (see Appendix T.1). This restates the importance of the firm's knowledge for its knowledge accumulation process.

In this knowledge accumulation process, because of summation, the productivity of researchers increases linearly with knowledge licensed from an additional high-tech firm. This means that the variety of knowledge matters in this setup. Such a formulation can

Appendix E.1 analyzes the case when firms cooperate in R&D and compete in the product market.

[10] This R&D process leads to scale effects. Jones (1995) argues against scale effects, and many papers following that argument present frameworks which eliminate these effects (e.g., Young, 1998; Peretto and Smulders, 2002). This paper maintains the current framework for its analytical simplicity. Although, some of the results regarding growth rates will not generalize in "second generation" growth models such as Jones (1995), they can generalize in "third generation" models such as Young (1998) where labor allocations matter.

be justified if there are significant complementarities among the knowledge of high-tech firms.

In the context of knowledge spillovers between countries, Rivera-Batiz and Romer (1991) and Grossman and Helpman (1995) also assume an additive structure for knowledge in the R&D process. They assume that in a country knowledge builds on the sum of the knowledge of all countries. Smulders and van de Klundert (1995) and Peretto (1996) have an additive structure in the context of knowledge spillovers among firms in an industry. In their setups, however, the degree of complementarity can vary.[11] Meanwhile, Peretto (1998a,b) have an additive structure in the context of knowledge spillovers among firms although they weight each firm's contribution to spillovers by its market share and fade away the complementarity. In this context, the major difference of R&D process (1.12) from the R&D processes used in these papers is the Cobb-Douglas combination of knowledge from different firms. Such a modelling assumption is particularly relevant in the context of licensing since it delivers well behaved demand functions. Further, such a formulation of the R&D process leads to a simple and analytically tractable inference. It ensures that a balanced growth path exists and allows this work to focus on the effect of the high-tech industry's market structure on innovation in that industry through competitive pressure.

Further, it might seem brave to assume that knowledge accumulation in a single firm can have non-decreasing returns. In this respect, a high-tech firm can be a firm that started with tabulating machines and reached the point of producing supercomputers and artificial intelligence systems (i.e., IBM). This assumption can be relaxed setting $u_{j,j} \equiv 0$ in square brackets in (1.12). In such a case, knowledge licensing (or exchange of knowledge) is a necessary condition to ensure non-decreasing returns to knowledge accumulation and positive growth in the long run (Appendix E.3 offers the main properties of the model when $u_{j,j} \equiv 0$).

One way to think about this setup is that each high-tech firm can license the patented knowledge of other firms in order to generate its own patented knowledge that helps to improve its production or output. The firm does not use knowledge that it licensed directly in the production of its high-tech good because that knowledge needs to be combined with its own and that requires investments in terms of hiring researchers (and time). The latter seems plausible for technologically sophisticated (e.g., high-tech) goods.

[11] Appendix E.2 and Appendix E.6 offer generalizations of the R&D process employed in this paper. Appendix E.2 incorporates knowledge spillovers and depreciation in this process. Meanwhile, Appendix E.6 offers the main properties of the model for more general CES formulation of this process where the degree of complementarity varies.

Knowledge Spillovers: In this case (S.2) there are knowledge spillovers among high-tech firms. In high-tech firm j the researchers combine the knowledge that spills over from other high-tech firms with the knowledge available in the firm while generating new knowledge. I assume also that the researchers do not fully internalize the use of current knowledge available in the firm and have external benefits from it. This assumption is merely for technical convenience. It helps to focus on the effect of market structure of the high-tech industry on innovation through competitive pressure. In particular, under this assumption all firms have the same external returns, no matter what the size of their knowledge is relative to the stock of knowledge of all firms. Further, under this assumption symmetry can be maintained between this and previous setups. (Appendix E.3 relaxes this assumption and offers the main properties of the model.)

The knowledge accumulation process is

$$\dot{\lambda}_j = \xi \tilde{\Lambda} \lambda_j^{1-\alpha} L_{r_j}, \tag{1.13}$$

where I assume that in equilibrium $\tilde{\Lambda}$ is given by

$$\tilde{\Lambda} \equiv \sum_{i=1}^{N} (u_{i,j}\lambda_i)^{\alpha}, \tag{1.14}$$

$$u_{i,j} \equiv 1.$$

An interpretation of this case is that there are knowledge externalities/spillovers within high-tech firms, and there is a market for knowledge where the potential licensees have a right to make a 'take it or leave it' offer. The licensees under this assumption receive the knowledge at no cost if the supply of knowledge is not elastic (i.e., $u_{i,j} \equiv 1$, and there are knowledge spillovers). The supply is necessarily inelastic if licensors do not have trade-offs and/or costs associated with licensing knowledge. It seems natural to assume that once knowledge is created, its supply entails virtually no costs. Meanwhile, there would be no trade-offs if licensors do not take into account that the knowledge they license is used for business stealing: The licensees use it in order to reduce their prices and steal market share. I assume that licensors do not take into account this effect.

Such an assumption is not new to this line of literature. Many papers (e.g., van de Klundert and Smulders, 1997) assume that the originators of knowledge spillovers (here, high-tech firms) do not internalize the effect of spillovers (here, licensed knowledge) on other's knowledge accumulation and production processes. This assumption helps to avoid complications in differential games arising from the dependence of the current choice on the entire future (or history) of states.[12] Further, in the frames of this model this assumption is necessary in order to give such a market-based interpretation to knowledge spillovers, which links this setup (S.2) with the previous one (S.1).

In this model, similar to λ, the design of a high-tech good can be interpreted as knowledge/a patent. In order to guarantee that high-tech firms have incentives to innovate it needs to be assumed that (at least for sometime) the knowledge on the design of high-tech goods does not spill over or cannot be used by other firms without appropriate compensation. Any high-tech firm, nevertheless, could sell the design of its high-tech good at market value: the discounted sum of profit streams earned selling the high-tech good.[13] Therefore, the market structure of knowledge on the production process or the quality of high-tech goods λ, where the licensors have a right to make a 'take it or leave it' offer seems to be more appropriate in such a setup.

In this model λ can also be viewed as a patent on the production process or the quality of the product. Such market-based interpretations are then appropriate if, for example, there is strong enforcement of intellectual property rights and patent infringements are detectable. Given the recent history of the high number of patent infringement lawsuits in high-tech industries, both assumptions seem to be plausible.

No Exchange of Knowledge: In this case (S.3), there is no exchange of knowledge among high-tech firms. Moreover, to maintain symmetry between this and previous setups, I assume that in the process of generating new knowledge, researchers do not fully internalize the use of knowledge available in the firm and have external benefits from it.

The knowledge accumulation is given by

$$\dot{\lambda}_j = \xi \tilde{\lambda} \lambda_j^{1-\alpha} L_{r_j}, \tag{1.15}$$

where $\tilde{\lambda}$ stands for the external benefits, and I assume that in equilibrium

$$\tilde{\lambda} \equiv \lambda_j^{\alpha}.\text{[14]} \tag{1.16}$$

It is clear that (1.12) and (1.13) reduce to (1.15) when there is no exchange of

[12] In this model, under this assumption, high-tech firms do not realize that the knowledge they accumulate enters the knowledge accumulation process of other high-tech firms and from the next instance augments their rivals' productivity. If they realized that, then by integrating over the (future) changes of knowledge of their rivals, they could track how their current investment in knowledge affects the productivity and market share of their rivals in the future.

[13] This simply implies that the name of the high-tech firm does not matter.

[14] van de Klundert and Smulders (1997) have a similar formulation for the knowledge accumulation process. Peretto (1998a,b) also have a similar knowledge accumulation process though these papers assume that $\alpha = 1$. This implies that knowledge in the R&D process is a pure externality.

knowledge among high-tech firms [i.e., (1.12) and (1.15) are equivalent if $u_{i,j} = 0$ for $\forall i \neq j$ and limiting case $\alpha = 0$; (1.13) and (1.15) are equivalent if $u_{i,j} = 0$ for $\forall i \neq j$.] Therefore, the comparison between results for knowledge accumulation processes (1.12), (1.13), and (1.15) can highlight the effect of knowledge exchange among high-tech firms. Further, the knowledge accumulation process (1.15) might be interpreted as if the exchange of knowledge among high-tech firms is banned (e.g., because of antitrust concerns), or it is made very costly.

Optimal Problem

The revenues of high-tech firm j are gathered from the supply of its high-tech good and when there is knowledge licensing (S.1) from the supply of its knowledge ($u_{j,i}\lambda_j; \forall i \neq j$). The costs are the labor compensations and license fees in case where there is knowledge licensing. The high-tech firm maximizes the present discounted value V of its profit streams subject to (1.7), (1.11), and either (1.12), or (1.13), or (1.15). Under Cournot competition, the high-tech firm chooses the supply of its product (i.e., L_{x_j}) given the (inverse) demand for it. In contrast, under Bertrand competition, the firm chooses the price of its product (i.e., p_{x_j}) given the demand for it.[15]

Formally, the problem of the high-tech firm is

$$\max_{\substack{\textit{Cournot}:\ L_{x_j}, L_{r_j}, \{u_{j,i}, u_{i,j}\}_{i=1;(i\neq j)}^{N} \\ \textit{Bertrand}:\ p_{x_j}, L_{r_j}, \{u_{j,i}, u_{i,j}\}_{i=1;(i\neq j)}^{N}}} V_j\left(\bar{t}\right) = \int_{\bar{t}}^{+\infty} \pi_j\left(t\right) \exp\left[-\int_{\bar{t}}^{t} r\left(s\right) ds\right] dt \tag{1.17}$$

$s.t.$

$$(1.7), (1.11) \text{ and either } (1.12), \text{ or } (1.13), \text{ or } (1.15),$$

where $\bar{t}$ is the entry date and

$$\begin{aligned} \pi_j &= p_{x_j} x_j - w\left(L_{x_j} + L_{r_j}\right) \\ &+ \left[\sum_{i=1, i\neq j}^{N} p_{u_{j,i}\lambda_j}\left(u_{j,i}\lambda_j\right) - \sum_{i=1, i\neq j}^{N} p_{u_{i,j}\lambda_i}\left(u_{i,j}\lambda_i\right)\right]. \end{aligned} \tag{1.18}$$

In profit function π_j the term in square brackets stands for knowledge licensing, and $p_{u_{j,i}\lambda_j}$ and $p_{u_{i,j}\lambda_i}$ are the prices of $u_{j,i}\lambda_j$ and $u_{i,j}\lambda_i$.

The solution of the optimal problem implies that the supply of high-tech good x_j and the demand for labor for knowledge accumulation are

$$\left[L_{x_j}\right] : w = \lambda_j p_{x_j}\left(1 - \frac{1}{e_j}\right), \tag{1.19}$$

[15] Cournot and Bertrand types of competition are modeled as in van de Klundert and Smulders (1997).

$$\left[L_{r_j}\right] : w = q_{\lambda_j} \frac{\dot{\lambda}_j}{L_{r_j}}, \tag{1.20}$$

where e_j is the elasticity of substitution between high-tech goods perceived by the high-tech firm, and q_{λ_j} is the shadow value of knowledge accumulation.

The perceived elasticity of substitution (e_j) varies with competition type. It can be shown that under Bertrand competition

$$e_j^{BR} \equiv e_j = \varepsilon - \left[\frac{(\varepsilon - 1)\, p_{x_j}^{1-\varepsilon}}{\sum_{i=1}^{N} p_{x_i}^{1-\varepsilon}} \right], \tag{1.21}$$

and under Cournot competition

$$e_j^{CR} \equiv e_j = \varepsilon \left\{ 1 + \left[(\varepsilon - 1) \frac{x_j^{\frac{\varepsilon-1}{\varepsilon}}}{\sum_{i=1}^{N} x_i^{\frac{\varepsilon-1}{\varepsilon}}} \right] \right\}^{-1}. \tag{1.22}$$

The terms in square brackets in (1.21) and (1.22) measure the impact of other high-tech firms on the demand of high-tech firm j. In other words, they measure the extent of strategic interactions among high-tech firms. Moreover, these terms indicate the difference between the perceived elasticity of substitution (e) and the actual elasticity of substitution (ε). Therefore, they indicate some of the distortions in the economy which stem from imperfect competition with a finite number of high-tech firms. In a symmetric equilibrium, when the number of firms increases, these distortions tend to zero since the terms in square brackets tend to zero.

When there is knowledge licensing (S.1), the returns on knowledge accumulation are

$$[\lambda_j] : \frac{\dot{q}_{\lambda_j}}{q_{\lambda_j}} = r - \left(\frac{e_j^k - 1}{e_j^k} \frac{p_{x_j}}{q_{\lambda_j}} L_{x_j} + \frac{\partial \dot{\lambda}_j}{\partial \lambda_j} + \sum_{i=1, i \neq j}^{N} \frac{p_{u_{j,i} \lambda_j} u_{j,i}}{q_{\lambda_j}} \right), \tag{1.23}$$
$$k = CR, BR,$$

where the first term in brackets is the benefit from accumulating knowledge in terms of increased output. The second term is the benefit in terms of a higher amount of knowledge available for subsequent knowledge accumulation,

$$\frac{\partial \dot{\lambda}_j}{\partial \lambda_j} = \xi \left[1 + (1 - \alpha) \sum_{i=1, i \neq j}^{N} \left(\frac{u_{i,j} \lambda_i}{\lambda_j} \right)^{\alpha} \right] L_{r_j}. \tag{1.24}$$

In turn, the third term in brackets is the benefit in terms of the increased amount of knowledge that can be licensed.

The demand for and the supply of knowledge in this case are

$$[u_{i,j}] : p_{u_{i,j}\lambda_i} = q_{\lambda_j}\xi\alpha\left(\frac{\lambda_j}{u_{i,j}\lambda_i}\right)^{1-\alpha} L_{r_j},\ \forall i \neq j, \tag{1.25}$$

$$[u_{j,i}] : u_{j,i} = 1,\ \forall i \neq j, \tag{1.26}$$

which means that the firm has a downward sloping demand for knowledge and licenses/supplies all its knowledge.

When there are knowledge spillovers among high-tech firms (S.2), the returns on knowledge accumulation are given by (1.23), but

$$p_{u_{j,i}\lambda_j} = 0,\ \forall i, \tag{1.27}$$

and

$$\frac{\partial\dot{\lambda}_j}{\partial\lambda_j} = \xi\left(1-\alpha\right)\left[\sum_{i=1}^{N}\left(\frac{\lambda_i}{\lambda_j}\right)^{\alpha}\right] L_{r_j}. \tag{1.28}$$

The first expression means that the licensees receive knowledge/patents for free [i.e., (1.26) holds, and $u_{i,j} \equiv 1$.] In turn, there is a difference between (1.24) and (1.28) because in S.1 there are no knowledge externalities within high-tech firms.

In turn, if there is no exchange of knowledge among high-tech firms (S.3), the returns on knowledge accumulation are given by (1.23), where the third term is absent and

$$\frac{\partial\dot{\lambda}_j}{\partial\lambda_j} = \xi\left(1-\alpha\right) L_{r_j}.\text{[16]} \tag{1.29}$$

The expression for the price of knowledge (1.25) indicates that licensees pay a fixed fee for it. The fee is equal to their marginal valuation, which includes all future benefits from using that knowledge for augmenting their current knowledge. Therefore, licensors appropriate all the benefit from licensing knowledge (i.e., they make the ‘take it or leave it’ offer). With a continuous accumulation of knowledge, as given by (1.12), at each and every instant, the licensees acquire new knowledge at a fixed fee.

It is clear from (1.23) that I have assumed that the firm does not take into account the effect of accumulating knowledge on the price of knowledge $p_{u_{j,i}\lambda_j}$. From (1.25), it follows that $p_{u_{j,i}\lambda_j}$ declines with λ_j. In this sense, I focus on a perfect market for knowledge (where the price of knowledge is equal to its marginal value, and licensors appropriate all benefit.) An alternative assumption would be that the firm internalizes this effect. In such a circumstance, there is an additional term in (1.23): the derivative

[16] Clearly, such a result holds when either $u_{j,i} = 0$ or $p_{u_{j,i}\lambda_j} = +\infty$ for $\forall i \neq j$.

of $p_{u_{j,i}\lambda_j}$ with respect to λ_j.

Even though taking this effect into account changes the incentives of accumulating knowledge, it does not affect the supply of knowledge (1.26) because supply entails no costs and/or trade-offs.[17]

In the frames of this model the assumption that licensors do not take into account that their knowledge is used for business stealing amounts to assuming that firm j takes as exogenous q_{λ_i} for any i different than j. This is in line with assuming that it takes as exogenous $p_{u_{j,i}\lambda_j}$.

Finally, in equilibrium there is no difference if high-tech firms license their knowledge in return for wealth transfer or the knowledge of other firms (plus-minus a fee.) Therefore, knowledge licensing among high-tech firms can also be thought to resemble patent consortia or pools.

Firm Entry

I focus on two regimes of "entry" into the high-tech industry. In the first regime, there are exogenous barriers to entry (i.e., there is no entry), and all firms in the market are assumed to have entered at time 0 ($t = 0$.) In the second, there are no barriers to entry into the high-tech industry. Moreover, entry entails no costs. To a certain extent, such a setup might be more appropriate for modelling an exit rather than an entry. This setup delivers tractable results for the case when there is no exchange of knowledge among high-tech firms. Later in the text, I offer and highlight the balanced growth path properties of a setup where entry entails endogenous costs for the cases when there is an exchange of knowledge among high-tech firms.

In order to support symmetric equilibrium, I assume that the entrants into the industry have the highest productivity available at the entry date. Further, I assume that high-tech firms do not coordinate on their entry and exit strategies.

1.3 Features of the Dynamic Equilibrium

I restrict the attention to a symmetric equilibrium in the high-tech industry.

The growth rate of knowledge/productivity when there is an exchange of knowledge among high-tech firms (S.1-2) is given by (1.12), (1.13), and (1.14). When there is no exchange of knowledge (S.3), it is given by (1.15). Denoting the growth rates of

[17] Appendix E.4 derives the model under this alternative assumption. It shows that high-tech firms innovate less if they take into account the effect of knowledge accumulation on the price of knowledge because innovating decreases their returns on knowledge licensing.

variables by letter g, the growth rate of knowledge can be written as

$$g_\lambda = \xi I^N_{S.1-2} L_r \tag{1.30}$$

for all S.1-3 cases, where

$$I^N_{S.1-2} = \begin{cases} 1 \; for \; S.3, \\ N \; otherwise. \end{cases}$$

Parameter $I^N_{S.1-2}$ shows the extent to which the availability of complementary knowledge can improve the R&D process when there is an exchange of knowledge compared to when there is none.

The (internal) rate of return on knowledge accumulation can be derived from the optimal rules of the high-tech firm (1.19), (1.20), and (1.23)-(1.29). It is given by

$$g_{q_\lambda} = r - g_\lambda \left(\frac{L_x}{L_r} + 1 - \alpha I^1_{S.2-3} \right), \tag{1.31}$$

where

$$I^1_{S.2-3} = \begin{cases} 0 \; for \; S.1, \\ 1 \; otherwise. \end{cases}$$

This parameter indicates the magnitude of not appropriated returns on R&D, and in that context, it can be called a monetization indicator.

The expression for the rate of return on knowledge accumulation (1.31) determines the allocation of labor to R&D in a high-tech firm relative to the allocation of labor to production. Here, this ratio does not (explicitly) depend on competitive pressure in the industry because high-tech firms decide on the division of labor between production and R&D internally, and L_x and L_r are paid the same wage.

From the conditions that follow from a high-tech firm's optimal problem (1.6)-(1.9), follows a relationship between NL_x and L_Y,

$$NL_x = \frac{\sigma}{1-\sigma} b^k L_Y, \tag{1.32}$$

where

$$b^k = \frac{e^k - 1}{e^k}. \tag{1.33}$$

This relationship shows the effect of price setting by high-tech firms. In symmetric equilibrium the perceived elasticities of substitution are

$$e^{BR} = \varepsilon - \frac{\varepsilon - 1}{N}, \tag{1.34}$$

$$e^{CR} = \frac{\varepsilon}{1 + \frac{\varepsilon - 1}{N}}. \tag{1.35}$$

Therefore, competition is tougher and mark-ups are lower if high-tech firms compete in prices, $e^{BR} > e^{CR}$. Moreover, mark-ups decline with the number of firms N and ε. This implies that the ratio $\frac{L_Y}{NL_x}$ declines with N, ε and with the toughness of competition because as the competitive pressure increases the relative price of x declines, which increases NL_x. Meanwhile, final goods producers substitute X for L_Y, which reduces L_Y.

From (1.32) it is also clear that $\frac{L_Y}{NL_x}$ declines with σ and does not depend on μ. The first result holds because higher σ implies a higher marginal product of X and a lower marginal product of L_Y. The second result stems from the assumption that efficiency gains due to external effects are Hicks-neutral.

The relationship between NL_x and L_Y (1.32) together with labor market clearing condition,

$$L = L_Y + N\left(L_x + L_r\right), \tag{1.36}$$

implies a relationship between NL_x and NL_r,

$$NL_x = D^k\left(L - NL_r\right), \tag{1.37}$$

where D^k measures the effect of competitive pressure in the high-tech industry on allocations of the labor force:

$$D^k = \frac{\sigma\left(e^k - 1\right)}{e^k - \sigma}.^{18} \tag{1.38}$$

Meanwhile, in the final goods market, since either there is no entry or entry entails no costs and the assets in this economy are the high-tech firms, it has to be the case that

$$Y = C, \tag{1.39}$$

which means that all final output is consumed.

Entry Regime 1: Exogenous Barriers to Entry

I take $N > 1$ and allow profits π in (1.18) to be negative. This is needed in order to characterize the behavior of labor force allocations and the growth rate of knowledge for any $N > 1$, ε, and type of competition, and can be supported by subsidies, for example.

[18] Appendix E.5 shows that in the limiting case when $\sigma = 1$, competitive pressure in the high-tech industry does not matter for these allocations because in such a case there are no relative price distortions.

Decentralized Equilibrium

Since there are exogenous barriers to entry the number of firms is fixed,

$$\dot{N} = g_N = g_{\frac{e^k - 1}{e^k}} = 0.$$

Moreover, from (1.39) it follows that consumption and final output grow at the same rate,

$$g_C = g_Y. \tag{1.40}$$

Let the consumers be sufficiently patient so that $\theta \geq 1$, which is a standard stability condition in multi-sector endogenous growth models and seems to be the empirically relevant case.

Proposition 1. *Let the following parameter restriction hold for any sufficiently small N:*

$$\xi D^k \frac{I^N_{S.1-2}}{N} L > \rho. \tag{1.41}$$

In such a case, in a decentralized equilibrium in all S.1-3 cases, the economy makes a discrete "jump" to a balanced growth path where labor force allocations, and growth rates of knowledge/productivity and final output are given by

$$NL_r^{NE} = \frac{N}{\xi I^N_{S.1-2}} \frac{\xi D^k \frac{I^N_{S.1-2}}{N} L - \rho}{(\theta - 1)(\sigma + \mu) + \alpha I^1_{S.2-3} + D^k}, \tag{1.42}$$

$$NL_x^{NE} = D^k \frac{\left[(\theta - 1)(\sigma + \mu) + \alpha I^1_{S.2-3}\right] L + \frac{N}{\xi I^N_{S.1-2}} \rho}{(\theta - 1)(\sigma + \mu) + \alpha I^1_{S.2-3} + D^k}, \tag{1.43}$$

$$L_Y^{NE} = \frac{1 - \sigma}{\sigma b^k} D^k \frac{\left[(\theta - 1)(\sigma + \mu) + \alpha I^1_{S.2-3}\right] L + \frac{N}{\xi I^N_{S.1-2}} \rho}{(\theta - 1)(\sigma + \mu) + \alpha I^1_{S.2-3} + D^k}, \tag{1.44}$$

and

$$g_Y^{NE} = (\sigma + \mu) g_\lambda^{NE}, \tag{1.45}$$

$$g_\lambda^{NE} = \frac{\xi D^k \frac{I^N_{S.1-2}}{N} L - \rho}{(\theta - 1)(\sigma + \mu) + \alpha I^1_{S.2-3} + D^k}. \tag{1.46}$$

Proof. See Proofs Appendix. □

I use NE superscript for equilibrium labor force allocations and growth rates to denote the case when there is no entry. Parameter restriction (1.41) ensures that the inter-temporal benefit from allocating the labor force to R&D outweighs its cost.

If parameter restriction (1.41) does not hold, high-tech firms do not innovate. Therefore, the economy is static ($g_\lambda = g_Y = 0$), and the labor force allocations in all S.1-3 cases are given by

$$NL_r^{NE} = 0, \tag{1.47}$$

$$NL_x^{NE} = D^k L, \tag{1.48}$$

$$L_Y^{NE} = \frac{1-\sigma}{\sigma b^k} NL_x^{NE}. \tag{1.49}$$

This restriction may not hold for large N if there is no exchange of knowledge among high-tech firms (S.3) since when $I_{S.1-2}^N = 1$, the left-hand side of the inequality tends to zero as N increases. When there is no exchange of knowledge, therefore, if N is sufficiently large, then the economy is on a balanced growth path where $g_\lambda = g_Y = 0$, and labor force allocations are given by (1.47)-(1.49). In this respect, if parameter restriction (1.41) holds for any sufficiently small $N > 1$, then it always holds in cases where there is an exchange of knowledge among high-tech firms (S.1-2) because when $I_{S.1-2}^N = N$, the left-hand side of the inequality increases with N.

Without loss of generality, hereafter, I assume that (1.41) holds for any finite N and does not hold when there is no knowledge exchange among high-tech firms (i.e., $I_{S.1-2}^N = 1$) if N is arbitrarily large/infinite ($N = +\infty$).

Proposition 2. *Let parameter restriction (1.41) hold. If high-tech firms choose not to engage in R&D, then labor force allocations are given by (1.47)-(1.49). Moreover, the value of high-tech firms is higher if none of the high-tech firms engage in R&D.*

Proof. See Proofs Appendix. □

I further assume that high-tech firms cannot collude and not innovate (for example, due to antitrust regulation or the non-sustainability of collusion). In this respect, in a decentralized equilibrium, each high-tech firm prefers to engage in R&D because R&D reduces its marginal cost. Therefore, *ceteris paribus* R&D allows the firm to lower its price and capture more market.

Social Optimum

The hypothetical Social Planner selects the paths of quantities so as to maximize the lifetime utility of the household (3.11). The Social Planner internalizes all externalities and solves the following problem.

$$\max_{L_x, L_r} U = \int_0^{+\infty} \frac{C_t^{1-\theta} - 1}{1-\theta} \exp(-\rho t)\, dt \tag{1.50}$$

s.t.

$$C = \left(N^{\frac{\varepsilon}{\varepsilon-1}} \lambda L_x\right)^{\sigma+\mu} \left[L - N\left(L_x + L_r\right)\right]^{1-\sigma}, \tag{1.51}$$

$$\dot{\lambda} = \xi I^N_{S.1-2}\lambda L_r, \tag{1.52}$$
$$\lambda(0) > 0 - given.$$

The Social Planner's optimal choices for L_x and L_r are given by

$$[L_x] : NL_x = D^{SP}(L - NL_r), \tag{1.53}$$
$$[L_r] : q_\lambda \xi I^N_{S.1-2}\lambda = \frac{(1-\sigma)N}{L - N(L_x + L_r)}C^{1-\theta}, \tag{1.54}$$

where

$$D^{SP} = \frac{\sigma + \mu}{1 + \mu}, \tag{1.55}$$

and I use SP superscript to make a distinction between the Social Planner's choice and decentralized equilibrium outcomes. Meanwhile, the socially optimal returns on knowledge accumulation are given by

$$[\lambda] : \dot{q}_\lambda = q_\lambda \rho - \left[q_\lambda \xi I^N_{S.1-2}L_r + (\sigma + \mu)\lambda^{-1}C^{1-\theta}\right]. \tag{1.56}$$

The optimal choice of L_x (1.53) together with labor market clearing condition (1.36) implies that

$$NL_x = \frac{1+\mu}{1-\sigma}D^{SP}L_Y. \tag{1.57}$$

This relation is the counterpart of (1.32) in a decentralized equilibrium.

Proposition 3. *Let the following parameter restriction hold for any sufficiently small N:*

$$\xi D^{SP}\frac{I^N_{S.1-2}}{N}L > \rho. \tag{1.58}$$

In such a case, the Social Planner chooses labor force allocations such that the economy, where there is "no entry", makes a discrete jump to a balanced growth path, where

$$NL_r^{NE,SP} = \frac{N}{\xi I^N_{S.1-2}}\frac{\xi D^{SP}\frac{I^N_{S.1-2}}{N}L - \rho}{(\theta - 1)(\sigma + \mu) + D^{SP}}, \tag{1.59}$$
$$NL_x^{NE,SP} = D^{SP}\frac{(\theta - 1)(\sigma + \mu)L + \frac{N}{\xi I^N_{S.1-2}}\rho}{(\theta - 1)(\sigma + \mu) + D^{SP}}, \tag{1.60}$$
$$L_Y^{NE,SP} = \frac{1-\sigma}{\sigma + \mu}D^{SP}\frac{(\theta - 1)(\sigma + \mu)L + \frac{N}{\xi I^N_{S.1-2}}\rho}{(\theta - 1)(\sigma + \mu) + D^{SP}}, \tag{1.61}$$

and

$$g_Y^{NE,SP} = (\sigma + \mu)g_\lambda^{NE,SP}, \tag{1.62}$$

$$g_{\lambda}^{NE,SP} = \frac{\xi D^{SP} \frac{I_{S.1-2}^{N}}{N} L - \rho}{(\theta - 1)(\sigma + \mu) + D^{SP}}. \tag{1.63}$$

Proof. See Proofs Appendix. □

Parameter restriction (1.58) necessarily holds as long as (1.41) holds since $D^{SP} > D^k$. As in a decentralized equilibrium, this inequality states that the benefit from R&D outweighs its cost.

Given that C in (1.51) satisfies Inada conditions, no corner solutions in terms of NL_x or L_Y satisfy the Social Planner's optimal problem.

Proposition 4. *Meanwhile, if (1.58) holds, no corner solutions in terms of NL_r satisfy the Social Planner's optimal problem. However, in case parameter restriction (1.58) does not hold, the Social Planner sets*

$$NL_r = 0, \tag{1.64}$$

and the remaining labor force allocations according to

$$NL_x^{NE,SP} = D^{SP} L, \tag{1.65}$$

and

$$L_Y^{NE,SP} = \frac{1 - \sigma}{\sigma + \mu} D^{SP} L. \tag{1.66}$$

Proof. See Proofs Appendix. □

This parameter restriction does not hold if N is arbitrarily large/infinite and there is no knowledge exchange in economy (S.3). It holds, however, for any N in cases where there is an exchange of knowledge (S.1-2) since I have assumed that (1.41) holds.

I further assume that the Social Planner can choose between S.1-2 and S.3 cases. In terms of policies implemented by a government in a decentralized equilibrium this corresponds to motivating or banning a knowledge exchange in the economy.[19] Clearly, the Social Planner prefers S.1-2 over S.3 since it could set the same labor force allocations and have higher economic growth in S.1-2 cases. Therefore, in this sense it is socially desirable to have exchange of knowledge in the economy.

Comparative Statics and Comparisons

Within the decentralized equilibrium outcomes, first, I discuss the case when the number of high-tech firms N is finite ($N < +\infty$). Next, I discuss the limiting case when

[19] An example for such policy/action is the establishment of the Radio Corporation of America (RCA Corporation) that fostered cross-licensing in the telecommunications industry in the United States.

the number of high-tech firms is infinite ($N = +\infty$) and, therefore, (1.41) does not hold if there is no exchange of knowledge among high-tech firms (S.3). At the end of the section, I compare the decentralized equilibrium allocations and growth rates with the Social Planner's choice.

Proposition 5. *In all S.1-3 cases, the growth rate of knowledge/productivity (g_λ) and the growth rate of final output (g_Y) increase with the elasticity of substitution between high-tech goods (ε). Moreover, g_λ and g_Y are higher under Bertrand competition, which is tougher than Cournot competition.*

Proof. These results follow from (1.33)-(1.35), (1.38), (1.45), and (1.46). □

The driver behind these results is the relative price distortions, which are due to price setting by high-tech firms. These distortions increase the demand for labor in final goods production. Increasing the elasticity of substitution or the toughness of competition reduces these distortions. The reduction of distortions motivates final goods producers to substitute (a basket of) high-tech goods for labor. Higher demand for high-tech goods and a higher amount of available labor increase the incentives of high-tech firms to conduct R&D. This increases g_λ and g_Y.

Corollary 1. *In this respect in all S.1-3, cases NL_r and NL_x grow and L_Y declines with the elasticity of substitution ε and the toughness of competition.*

Proof. This result follows from (1.42)-(1.44). □

The comparative statics with respect to the number of high-tech firms when there is an exchange of knowledge (S.1-2) are different from when there is no exchange of knowledge (S.3). The results are summarized in the following proposition.

Proposition 6. *When there is an exchange of knowledge among high-tech firms (S.1-2), labor force allocations NL_r and NL_x and growth rates g_λ and g_Y increase with the number of firms N, whereas L_Y declines with it. If there is no exchange of knowledge (S.3), however, this result does not hold if the number of firms is relatively high.*

Proof. These results follow from (1.42)-(1.46). □

The driver behind the first result is the reduction in relative price distortions (or the intensification of competition) that the higher number of high-tech firms brings with it. Meanwhile, the second result holds because increasing the number of high-tech firms, if there is no exchange of knowledge among high-tech firms (S.3), has two effects. It reduces the relative price distortions and the amount of labor force that can be devoted to R&D [see $\frac{I^N_{S.1-2}}{N}$ term in (1.46)]. The first effect motivates higher demand for NL_r and increases g_λ, whereas the second effect reduces NL_r and g_λ. The second effect is absent when there is an exchange of knowledge among high-tech firms (S.1-2) because increasing the number of high-tech firms also increases the amount of complementary knowledge made available by these firms. Clearly, the result that these effects exactly offset each other hinges on the functional form assumptions for knowledge accumulation processes (1.12), (1.13) and (1.14).[20]

Proposition 7.

- *When there is an exchange of knowledge among high-tech firms (S.1-2),* g_λ *and* g_Y *are concave functions of the number of firms* N*.*
- *When there is no exchange of knowledge (S.3), the derivative of* g_λ*, as well as* g_Y*, with respect to* N *is positive when* N *is close to* 1*, and it is negative for any* N *greater than* 2*.*

Proof. These results follow from (1.46), and when there is a knowledge exchange among high-tech firms, $I^N_{S.1-2} = N$, whereas $I^N_{S.1-2} = 1$ if there is no knowledge exchange. □

The first part of this proposition holds because competition intensifies more from adding a firm if there are few high-tech firms. Meanwhile, the second part holds because when there is no exchange of knowledge (S.3) at the higher levels of market concentration/lower levels of competition ($N \approx 1$), the positive effect of higher competition is dominant. Meanwhile, at the lower levels of market concentration/higher levels of competition ($N > 2$), the negative effect of the reduction in the amount of resource for R&D is dominant. The full characterization of the behavior of g_λ and g_Y for $N \in (1, 2)$ is not so straightforward, however, because of the high non-linearity of g_λ in that interval. In the neighborhood of $N = 1$, the growth rate of knowledge/productivity g_λ is increasing and concave in N, and after a tipping point from $(1, 2)$, it becomes convex and decreasing.[21]

Proposition 8.

- *In all S.1-3 cases labor force allocations* NL_r *and* NL_x *and growth rates* g_λ *and* g_Y *increase with* σ*, whereas* L_Y *declines with it. In contrast,* g_λ *and* NL_r *decline with* μ *and* g_Y*,* NL_x*, and* L_Y *increase with it.*

---

[20] One way to relax this assumption is to multiply (1.12) and (1.14) by a function $F(N)$. Appendix E.6 offers the main properties of such a generalization of the model and sufficient conditions to have g_λ increasing in N.

[21] This result implies that when there is no exchange of knowledge among high-tech firms (S.3), there is an "inverted-U" shape relationship between g_λ and the number of firms N. A similar result can be obtained when there is an exchange of knowledge among high-tech firms (S.1-2) assuming fixed management costs as in van de Klundert and Smulders (1997), or that (1.12) and (1.14) increase less than linearly with N. The latter assumption would imply that the benefits from the availability of complementary knowledge are less than N.

- *When there are knowledge spillovers/externalities (S.2-3), NL_r, g_λ and g_Y decline with α, whereas NL_x and L_Y increase with it.*

Proof. These results follow from (1.42)-(1.46). □

The first result holds because higher σ increases the marginal product of high-tech goods bundle X and reduces the marginal product of the labor force employed in final goods production L_Y. Therefore, the demand for L_Y declines, and labor force allocations NL_x and NL_r increase. According to (1.45) and (1.46), this implies that g_λ and the growth rate of final output g_Y increase with σ. In contrast, higher μ does not affect the balance between the demand for X and L_Y and, in this sense, does not alter the production and R&D incentives of high-tech firms. Meanwhile, *ceteris paribus* it increases the growth rate of final output g_Y and equilibrium interest rate r [see (1.3)], which discourages investments in R&D. Lower NL_r implies a lower growth rate of knowledge/productivity g_λ. Finally, the second part of this proposition holds because where there are knowledge spillovers/externalities as α increases, the internalized returns on R&D decline, and firms invest less in R&D. Therefore, more labor force is allocated to production activities, and g_λ and g_Y decline.

In order to preserve space, hereafter, unless stated otherwise, I exclusively discuss the results for the growth rate of knowledge/productivity g_λ while keeping in mind that the growth rate of final output g_Y is proportional to it.

Corollary 2. *If the number of high-tech firms is arbitrarily large/infinite*

- *when there is an exchange of knowledge among high-tech firms (S.1-2), labor force allocations and growth rate g_λ are given by (1.42)-(1.44) and (1.46), where*

$$D^k \equiv D = \frac{\sigma(\varepsilon - 1)}{\varepsilon - \sigma};$$

- *when there is no exchange of knowledge among high-tech firms (S.3), $g_\lambda = 0$, and labor force allocations are given by (1.47)-(1.49), where $D^k \equiv D$.*

The first part of this corollary implies that when there is an exchange of knowledge among high-tech firms and $N = +\infty$, neither labor force allocations nor the growth rate of knowledge depend on the type of competition or the number of high-tech firms. It implies also that the remaining comparative statics stay intact in these cases. The second part of the corollary holds because when there is no exchange of knowledge among high-tech firms and $N = +\infty$, the parameter restriction (1.41) does not hold. It can be shown that in this case, NL_x increases and L_Y declines with σ and ε, and both NL_x and L_Y do not depend on the type of competition or parameters α and μ.

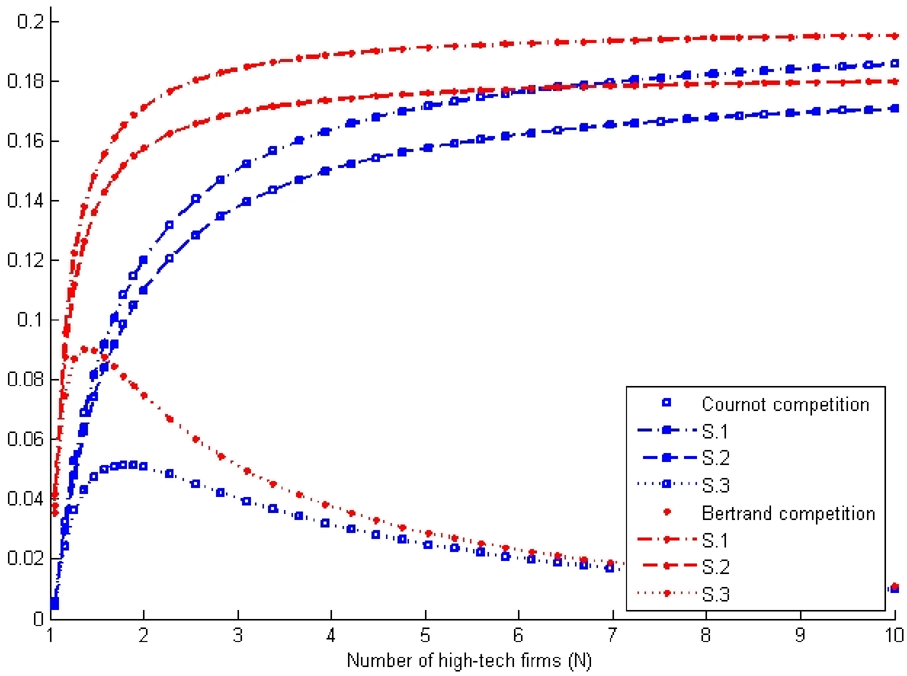
Corollary 3. *For both finite and infinite number of high-tech firms, the comparison between S.1-3 cases yields the following relationships.*

$$\begin{aligned} &NL_r^{NE,S.1} > NL_r^{NE,S.2} > NL_r^{NE,S.3}, \\ &NL_x^{NE,S.1} < NL_x^{NE,S.2} < NL_x^{NE,S.3}, \\ &L_Y^{NE,S.1} < L_Y^{NE,S.2} < L_Y^{NE,S.3}, \\ &g_\lambda^{NE,S.1} > g_\lambda^{NE,S.2} > g_\lambda^{NE,S.3}. \end{aligned} \tag{1.67}$$

This means that in the decentralized equilibrium with no entry, high-tech firms innovate the most when there is knowledge licensing (S.1). High-tech firms innovate the least if there is no exchange of knowledge among these firms (S.3). Therefore, for a given N, the growth rate of final output is the highest when there is knowledge licensing and the lowest when there is no exchange of knowledge among high-tech firms.

In order to further highlight the contrast between all knowledge accumulation/R&D setups (S.1-3) Figure 1.1 plots g_λ for parameter values $\theta = 4$, $\rho = 0.01$, $\sigma = 0.3$, $\mu = 0.01$, $\varepsilon = 4$, $L = 1$, $\xi = 1$, and $\alpha = 0.1$ and for Cournot and Bertrand types of competition.[22]

Figure 1.1: *The Growth Rate of Productivity in S.1-3 Cases*



Note: This figure plots g_λ as a function of N for parameter values $\theta = 4$, $\rho = 0.01$, $\sigma = 0.3$, $\mu = 0.01$, $\varepsilon = 4$, $L = 1$, $\xi = 1$, and $\alpha = 0.1$ and for Cournot and Bertrand types of competition.

[22]The parameter values were selected so that the growth rate of final output has a reasonable value.

Comparisons Between Decentralized Equilibrium and Socially Optimal Results: Different types of competitive pressure matter for these decentralized equilibria outcomes because of market interactions among high-tech firms. They do not matter, however, for the outcomes of the Social Planner's problem (1.59)-(1.63).

Corollary 4. *In contrast to the decentralized equilibrium results* NL_r^{SP}, NL_x^{SP}, g_λ, *and* g_Y *increase with* μ, *and* L_Y^{SP} *declines with this parameter.*

Proof. This result follows from (1.59)-(1.63). □

This result holds because the Social Planner internalizes μ, and a higher μ implies a higher marginal product of X.

Corollary 5. *For both finite and infinite* N, *the comparisons between decentralized equilibrium growth rates and allocations and socially optimal growth rates and allocations yield the following relationships.*

$$\begin{aligned}
&NL_r^{NE,SP,S.1-2} > NL_r^{NE,S.1},\\
&NL_x^{NE,SP,S.1-2} \lesseqgtr NL_x^{NE,S.3},\\
&NL_x^{NE,SP,S.1-2} \lesseqgtr NL_x^{NE,S.2},\\
&NL_x^{NE,SP,S.1-2} > NL_x^{NE,S.1},\\
&L_Y^{NE,SP,S.1-2} < L_Y^{NE,S.1},
\end{aligned}$$

and

$$g_\lambda^{NE,SP,S.1-2} > g_\lambda^{NE,S.1},$$

where $\lesseqgtr$ *indicates that the relation depends on model parameters.*

This means that in the decentralized equilibrium, the economy innovates less than what is socially optimal and therefore grows at a lower rate. Moreover, in the decentralized equilibrium, it fails to have socially optimal labor force allocations. The driver behind these results is relative price distortions and externalities. Due to these distortions, final goods producers substitute labor for high-tech goods, which lowers the output of high-tech firms and the number of researchers that high-tech firms hire. The externalities in R&D have an effect of similar direction. If such externalities are present, then high-tech firms do not fully internalize the returns on R&D. This reduces their incentives to invest in R&D, and they hire a lower number of researchers. Meanwhile, the externalities in final goods production increase the interest rate r. Since high-tech firms do not take into account these externalities, they invest less than it is socially optimal. Final goods producers also do not take into account these externalities. Therefore, they demand less than what is the socially optimal amount of high-tech goods.

The differences between socially optimal and decentralized equilibrium growth rates and labor force allocations in terms of relative price distortions and externalities in final goods production are summarized by D^k and D^{SP}. It is easy to notice that for a sufficiently high N

$$\lim_{\mu\to 0} D^{SP} = \lim_{\varepsilon\to +\infty} D^k.$$

This equality holds because for sufficiently high N, the limiting case $\varepsilon = +\infty$ would imply perfect competition in the high-tech industry. In such a limiting case, however, in the decentralized equilibrium, high-tech firms make zero profits and have no market incentives to innovate.

In this respect, if there are no subsidies that keep the profits of high-tech firms non-negative, the positive relationship between innovation and ε holds as long as high-tech firms have sufficient profits to cover the costs of R&D. The profits of high-tech firms and ε are inversely related. Once profits net of R&D expenditures are equal to zero, increasing ε reduces innovation to zero. Therefore, if there are no subsidies, the relationship between the intensity of product market competition (ε) and innovation has an "inverted-U" shape. Such a relation is consistent with Schumpeter's argument that firms need to be sufficiently big in order to innovate. Moreover, it is in line with the empirical findings of Aghion et al. (2005) and provides an alternative explanation for those findings.

Entry Regime 2: Cost-free Entry

In this section, I endogenize the number of firms assuming that entry cost is zero.

Decentralized Equilibrium

From (1.18), (1.19), and (1.31), it follows that the profits of a high-tech firm are

$$\pi = wL_x\left[\frac{1}{e^k-1} - \frac{g_\lambda}{r - g_{q_\lambda} - \left(1-\alpha I^1_{S.2-3}\right)g_\lambda}\right].$$

Given that the entry cost is zero, the condition that endogenizes the number of high-tech firms is $\pi = 0$.

Denote

$$\bar{\pi} = \frac{1}{e^k-1} - \frac{g_\lambda}{r - g_{q_\lambda} - \left(1-\alpha I^1_{S.2-3}\right)g_\lambda}. \tag{1.68}$$

Therefore,

$$\pi = 0 \Leftrightarrow \bar{\pi} = 0. \tag{1.69}$$

Proposition 9. *At time 0 ($t = 0$), N makes a discrete jump to the balanced growth path equilibrium level.*

Proof. See Proofs Appendix. □

This implies that in a decentralized equilibrium with cost-free entry, the economy is on a balanced growth path (for any $t > 0$), where

$$\dot{N} = g_N = g_{\frac{e^k - 1}{e^k}} = 0.$$

Therefore, labor force allocations and growth rate of knowledge/productivity are given by (1.42)-(1.44) and (1.46), where the number of high-tech firms N is endogenous.

In turn, N can be derived from the zero profit condition (1.69) and g_λ that solves the capital market equilibrium (1.46). The growth rate of productivity g_λ that solves the zero profit condition (1.69) is

$$g_\lambda = \frac{\rho}{e^k - 1 - \alpha I^1_{S.2-3} - (\theta - 1)(\sigma + \mu)}. \tag{1.70}$$

Let

$$\varepsilon - 1 - \alpha - (\theta - 1)(\sigma + \mu) > 0,$$

which implies that g_λ can be positive for a sufficiently large N or, equivalently, decentralized equilibrium can exist where high-tech firms innovate.

Hereafter, I call g_λ from (1.70) ZP– zero profit –and g_λ from (1.46) CME - capital market equilibrium. If $\alpha > 0$ and/or $\theta > 1$ the number of high-tech firms N that satisfies

$$e^k - 1 - \alpha - (\theta - 1)(\sigma + \mu) = 0$$

is strictly greater than 1. Denote it by N^*. For $N \in (1, N^*)$, it can be shown that g_λ in (1.70) or ZP is negative, decreasing, and a convex function of N, and

$$\lim_{N \to N^*-} g_\lambda = -\infty.$$

Meanwhile for $N > N^*$ it can be shown that ZP is positive, decreasing, and a convex function of N, and

$$\lim_{N \to N^*+} g_\lambda = +\infty.$$

Proposition 10. *In a decentralized equilibrium with endogenous entry, it cannot happen that $N \in (1, N^*)$.*

Proof. This is because for $N \in (1, N^*)$, high-tech firms do not innovate, which implies that the profit of each firm is

$$\pi = wL_x \frac{1}{e^k - 1} > 0.$$

Therefore, there will be entry that will increase the number of high-tech firms above N^*. □

Both CME and ZP are continuous functions of N for $N > N^*$, the values of CME are finite for any $N > 1$, and ZP is arbitrarily large around N^*. Therefore, at least for N sufficiently close to N^* it has to be the case that ZP is higher than CME. This means that decentralized equilibrium exists where high-tech firms innovate.

If ZP crosses CME from above, then the decentralized equilibrium determined by the intersection is stable in the sense that the entry of firms reduces $\bar{\pi}$ in (1.68) and exit increases it. The number of firms and the growth rate of productivity can be solved from the intersection of CME and ZP in such a case. Moreover, if at time 0 ($t = 0$) the number of high-tech firms is higher than (and in S.3, sufficiently close to) the number determined by the intersection of ZP and CME, then high-tech firms will exit the market until ZP and CME are equal. Considering such a setup, or exit of high-tech firms instead of entry, can support the zero entry costs assumption.

In order to have a meaningful equilibrium in each of the S.1-3 cases [i.e., (1.69) holds], I further assume that the parameters are such that N^{**} exists where ZP crosses CME under Cournot competition when there is no exchange of knowledge (S.3). Given that (1.46) shifts up and (1.70) shifts down with the elasticity of substitution ε, this can be equivalent to assuming that the elasticity of substitution ε is sufficiently high. It implies that ZP crosses CME in all the remaining S.1-3 cases.[23]

The previous section showed that if there is an exchange of knowledge (S.1-2), the growth rate of knowledge g_λ from (1.46), or CME, is a monotonically increasing function of N.

Corollary 6. *When there is an exchange of knowledge among high-tech firms (S.1-2), ZP crosses CME from above and the number of high-tech firms under Cournot and Bertrand types of competition can be found from*

$$e^k = \frac{\xi\sigma L \left[1 + \alpha I^1_{S.2-3} + (\theta - 1)(\sigma + \mu)\right]}{\xi\sigma L - \rho}, \tag{1.71}$$

where $k = CR, BR$ and e^{CR} and e^{BR} are given by (1.34) and (1.35). In turn, from

[23] van de Klundert and Smulders (1997) offer a model which resembles the case when there is no exchange of knowledge among high-tech firms (S.3). The authors assume parameter values such that ZP crosses CME from above. Clearly, such a set of parameter values is restrictive when there is an exchange of knowledge among high-tech firms (S.1-2).

(1.71) and (1.30), (1.36), (1.37), and (1.46) it follows that

$$g_{\lambda}^{CFE,S.1-2} = \frac{\xi\sigma L-\rho}{(\theta-1)(\sigma+\mu)+\alpha I_{S.2-3}^{1}+1}, \tag{1.72}$$

$$NL_{r}^{CFE,S.1-2} = \frac{1}{\xi}\frac{\xi\sigma L-\rho}{(\theta-1)(\sigma+\mu)+\alpha I_{S.2-3}^{1}+1}, \tag{1.73}$$

$$NL_{x}^{CFE,S.1-2} = \frac{1}{\xi}\frac{\xi\sigma L\left[(\theta-1)(\sigma+\mu)+\alpha I_{S.2-3}^{1}\right]+\rho}{(\theta-1)(\sigma+\mu)+\alpha I_{S.2-3}^{1}+1}, \tag{1.74}$$

and

$$L_{Y}^{CFE,S.1-2} = (1-\sigma)L, \tag{1.75}$$

where CFE stands for cost-free entry.

If there is no exchange of knowledge (S.3), however, CME is not a monotonic function for all N. It is a monotonically increasing function in the neighborhood of $N=1$ and a monotonically decreasing after some $N \in (1,2)$. Moreover, it is continuous and finite for any N and negative for $N=1$ and $N=+\infty$. Therefore, given that ZP is a monotonically decreasing function, and it is positive for any N, ZP crosses CME at least twice.

Corollary 7. *If there is no exchange of knowledge among high-tech firms, then the number of firms under Cournot and Bertrand types of competition can be found from*

$$e^{k} = \frac{\xi\sigma\frac{1}{N}L\left[1+\alpha+(\theta-1)(\sigma+\mu)\right]}{\xi\sigma\frac{1}{N}L-\rho}. \tag{1.76}$$

In turn, from (1.76) and (1.30), (1.36), (1.37), and (1.46), it follows that

$$g_{\lambda}^{CFE,S.3} = \frac{\xi\sigma\frac{1}{N}L-\rho}{(\theta-1)(\sigma+\mu)+\alpha I_{S.2-3}^{1}+1}, \tag{1.77}$$

$$NL_{r}^{CFE,S.3} = \frac{N}{\xi}\frac{\xi\sigma\frac{1}{N}L-\rho}{(\theta-1)(\sigma+\mu)+\alpha I_{S.2-3}^{1}+1}, \tag{1.78}$$

$$NL_{x}^{CFE,S.3} = \frac{N}{\xi}\frac{\xi\sigma\frac{1}{N}L\left[(\theta-1)(\sigma+\mu)+\alpha I_{S.2-3}^{1}\right]+\rho}{(\theta-1)(\sigma+\mu)+\alpha I_{S.2-3}^{1}+1}, \tag{1.79}$$

and

$$L_{Y}^{CFE,S.3} = (1-\sigma)L. \tag{1.80}$$

It is straightforward to show that (1.76) is a quadratic equation in N. This means that when there is no exchange of knowledge among high-tech firms (S.3), ZP crosses

CME twice. It does so from above and from below. The smaller root of (1.76) corresponds to the stable equilibrium, where ZP crosses CME from above. Meanwhile, the bigger root corresponds to the case where ZP crosses CME from below and the equilibrium is not stable. Denote it by N_2^{**}. If the economy starts with a number of firms greater or equal to N_2^{**}, then $\bar{\pi}$ does not decline to zero as N increases. In order to rule this out, I further assume that the economy starts with a number of high-tech firms that is lower than N_2^{**}. Therefore, depending on whether ZP is higher or lower than CME, firms exit or enter till ZP crosses CME from above.[24]

Social Optimum

In this case the hypothetical Social Planner solves the optimal problem (1.50) and chooses N.

The Social Planner's optimal choice for N when there is an exchange of knowledge (S.1-2) is given by

$$[N] : \frac{\sigma + \mu}{\varepsilon - 1} \frac{C^{1-\theta}}{N} \geq 0$$

or simply

$$N = +\infty, \tag{1.81}$$

whereas if there is no exchange of knowledge (S.3), it is given by

$$[N] : \frac{\sigma + \mu}{\varepsilon - 1} C^{1-\theta} \geq q_\lambda \xi \lambda L_r. \tag{1.82}$$

The former result (1.81) holds because if there is an exchange of knowledge, then $I^N_{S.1-2} = N$, and the Social Planner has no trade-offs while increasing N.[25] In contrast, if there is no exchange of knowledge, then $I^N_{S.1-2} = 1$, and it has a trade-off. A higher N implies a lower growth rate.

In order to solve the optimal control problem when there is an exchange of knowledge ($I^N_{S.1-2} = N$) with first order conditions, C needs to be re-scaled by N so that at time zero $C < +\infty$ (i.e., C needs to be divided to $N^{\frac{\sigma+\mu}{\varepsilon-1}}$).

Proposition 11. *The Social Planner selects labor force allocations and N such that the economy makes a discrete jump to a balanced growth path.*

- *If there is an exchange of knowledge, on this path, labor force allocations and the growth rate of knowledge g_λ are given by (1.59)-(1.61) and (1.63) and $N = +\infty$.*

[24] The functional forms of the knowledge accumulation process when there is an exchange of knowledge among high-tech firms (S.1-2), help to avoid this assumption.

[25] When there is an exchange of knowledge (S.1-2), the Social Planner selects at time zero $N = +\infty$ because of the assumption that firm entry or creating high-tech goods entails no costs. If there were costs associated with entry (or costs associated with maintaining the goods/firms as in van de Klundert and Smulders, 1997), the Social Planner might not select at time zero (or at any time) $N = +\infty$.

- *If there is no exchange of knowledge and (1.82) is binding, then*

$$N = \frac{\xi (\sigma + \mu)}{\rho} \frac{\varepsilon - 1 - (\theta - 1)(\sigma + \mu)}{\varepsilon (1 + \mu) - (1 - \sigma)} L, \tag{1.83}$$

$$g_{\lambda}^{CFE,SP,S.3} = \frac{\rho}{\varepsilon - 1 - (\theta - 1)(\sigma + \mu)}. \tag{1.84}$$

Proof. See Proofs Appendix. □

If there is no exchange of knowledge and (1.82) is binding, labor force allocations can be derived from (1.52), (1.53), (1.57), and (1.84), where the expression (1.84) is the counterpart of ZP (1.70) with $N = +\infty$ and $\alpha = 0$.

Comparing the lifetime utility of the household, it can be shown, however, that the Social Planner prefers to set $N = +\infty$ also when there is no exchange of knowledge. Therefore, (1.82) does not bind. The following proposition summarizes this result.

Proposition 12. *When there is no exchange of knowledge, the Social Planner sets*

$$N = +\infty,$$

$$g_{\lambda}^{CFE,SP,S.3} = NL_r^{CFE,SP,S.3} = 0, \tag{1.85}$$

$$NL_x^{CFE,SP,S.3} = D^{SP} L, \tag{1.86}$$

and

$$L_Y^{CFE,SP,S.3} = \frac{1 - \sigma}{\sigma + \mu} D^{SP} L. \tag{1.87}$$

Proof. See Proofs Appendix. □

As it was shown in the Social optimum section of Entry Regime 1, this implies that the Social Planner prefers when there is an exchange of knowledge (S.1-2) over no exchange of knowledge (S.3). This result is not stemming from the cost-free entry assumption. Even if there were fixed costs associated with entry, the Social Planner could set the number of firms in cases where there is an exchange of knowledge (S.1-2) equal to the number of firms it finds optimal when there is no exchange of knowledge (S.3). In such a circumstance according to (1.63), it would have a higher growth rate and, therefore, welfare in cases where there is an exchange of knowledge (S.1-2).

Comparative Statics and Comparisons

The following proposition establishes the comparative statics results for the number of high-tech firms.

Proposition 13.

- *In all S.1-3 cases, there are fewer high-tech firms in equilibrium under Bertrand competition than under Cournot competition. Further, the number of firms declines with* ε *and increases with* μ*.*

- *When there are knowledge spillovers/externalities (S.2-3), the number of firms increases with* α*. It does not depend on* α *in case when there is knowledge licensing (S.1).*

Proof. See Proofs Appendix. □

The number of firms declines with the toughness of competition and ε since tougher competition and higher ε imply lower mark-ups, which reduces $\bar{\pi}$ for a given N. In turn, it increases with μ since higher μ implies lower R&D investments (fixed costs), which increases $\bar{\pi}$ for a given N. A higher α when there are knowledge spillovers/externalities (S.2-3) also implies lower R&D investments. The comparative statics with respect to σ depend on the model parameters.

Corollary 8.
When there is an exchange of knowledge among high-tech firms (S.1-2), from (1.72)-(1.75) it follows that

- g_λ *and labor force allocations do not depend on competition type and* ε*.*

- g_λ *and* NL_r *decrease with* α *and* μ *and increase with* σ*,* NL_x *increases with these parameters,* L_Y *does not depend on* α *and* μ *and declines with* σ*, and according to (1.45),* g_Y *declines with* α *but increases with* σ *and* μ*.*

In turn, when there is no exchange of knowledge among high-tech firms (S.3), from (1.77)-(1.80) and Proposition 13 it follows that

- g_λ *and* NL_r *increase and* NL_x *declines with the toughness of competition and* ε*. Meanwhile,* L_Y *does not depend on the type of competition and* ε*.*

- g_λ *and* NL_r *decrease and* NL_x *increases with* α *and* μ*,* L_Y *does not depend on* α *and* μ *and declines with* σ*.*

When there is an exchange of knowledge (S.1-2), this corollary indicates that in-house R&D of high-tech firms does not depend on competitive pressures in the high-tech industry. Such a result holds because of two reasons. First, entry reduces the profits of high-tech firms to zero and makes labor force allocations in firms independent of the intensity and toughness of competition. Second, (1.12) and (1.13) are linearly increasing with the number of high-tech firms. This exactly offsets the decline in the amount of labor force that can be available to a high-tech firm for R&D as the number of high-tech firms grows and makes labor force allocation to R&D in the firm independent of the number of firms. (Appendix E.6 shows that for a more general formulation of the R&D process, this result might not hold.)

Meanwhile, when there is no exchange of knowledge, it is not straightforward to derive the relationships between g_λ, NL_r, and NL_x and σ and the relationships between g_Y and μ and σ. Using numerical methods, it is possible to show that these comparative statics depend on model parameters.[26]

The following corollary summarizes the comparisons among different settings for the R&D process.

Corollary 9. *Given that the number of firms is greater than* 1

$$g_\lambda^{CFE,S.1} > g_\lambda^{CFE,S.2} > g_\lambda^{CFE,S.3}, \tag{1.88}$$

$$NL_r^{CFE,S.1} > NL_r^{CFE,S.2} > NL_r^{CFE,S.3}, \tag{1.89}$$

$$NL_x^{CFE,S.1} < NL_x^{CFE,S.2} < NL_x^{CFE,S.3},$$

and

$$L_Y^{CFE,S.1} = L_Y^{CFE,S.1-2} = L_Y^{CFE,S.3}.$$

Given that R&D investments are fixed costs, this implies that there are more high-tech firms when there are knowledge spillovers among these firms (S.2) than when there is knowledge licensing (S.1). Moreover, there are more high-tech firms when there is no exchange of knowledge among these firms (S.3) compared to when there are knowledge spillovers (S.2), i.e.,

$$N^{CFE,S.3} > N^{CFE,S.2} > N^{CFE,S.1}.$$

These results show that high-tech firms innovate more when there is an exchange of knowledge compared to when there is none. Moreover, these firms innovate more in case when there is knowledge licensing compared to the case there are knowledge spillovers/externalities. Meanwhile, using (1.59)-(1.61), (1.63), (1.88), and (1.89), it can be shown that in all S.1-3 cases in a decentralized equilibrium with cost-free (endogenous) entry into the industry, the economy invests in R&D less than what is socially optimal. Therefore, it grows at a lower than socially optimal rate. Further, it fails to have the socially optimal number of high-tech firms.

[26]The intervals of parameter values used in numerical simulations are offered in Appendix E.8.

Policies leading to the first best outcome in a decentralized equilibrium

In this section, I offer policies that if implemented in a decentralized equilibrium will lead to the first best outcome. I assume that there is knowledge licensing in the decentralized equilibrium. This can amount to assuming that the government has motivated a knowledge exchange among high-tech firms that happens in a market where the licensors have the right to make a 'take it or leave it' offer (i.e., they have bargaining power.) In this respect, such an action is one of the necessary policy instruments for increasing welfare in the decentralized equilibrium.[27] As I show in Appendix E.8, this instrument alone cannot be sufficient, however. For example, in the decentralized equilibrium for sufficiently low values of α, welfare can be higher when there are knowledge spillovers (S.2) compared to when there is knowledge licensing (S.1).

I assume that the set of additional policy instruments includes marginal taxes on (or subsidies for) purchases of high-tech goods (τ_x) and high-tech firms' expenditures on buying knowledge (τ_λ). It also includes lump-sum transfers to high-tech firms (T_π) and households (T). The latter balances government expenditures.

Under such a policy from the final goods producer's problem, it follows that (1.7) and (1.10) need to be re-written as

$$x_j = X\left[\frac{P_X}{(1-\tau_x)\,p_{x_j}}\right]^{\varepsilon},$$
$$P_X X = (1-\tau_x)\sum_{i=1}^{N} p_{x_i} x_i.$$

In turn, the profit function of high-tech firm j is

$$\pi_j = p_{x_j} x_j - w\left(L_{x_j} + L_{r_j}\right) + \left[\sum_{i=1, i\neq j}^{N} p_{u_{j,i}\lambda_j}\left(u_{j,i}\lambda_j\right) - (1-\tau_\lambda)\sum_{i=1, i\neq j}^{N} p_{u_{i,j}\lambda_i}\left(u_{i,j}\lambda_i\right)\right] + T_\pi.$$

Therefore, the high-tech firm's demand for knowledge (1.25) needs to be re-written as

$$[u_{i,j}] : (1-\tau_\lambda)\,p_{u_{i,j}\lambda_i} = q_{\lambda_j}\xi\alpha\left(\frac{\lambda_j}{u_{i,j}\lambda_i}\right)^{1-\alpha} L_{r_j}, \ \forall i \neq j.$$

Considering symmetric equilibrium and combining these optimal rules with (1.6), (1.9), (1.24), and labor market clearing condition (1.36), this gives the counterparts to

[27] When there is no exchange of knowledge among high-tech firms there is no set of (orthodox) policy instruments in terms of welfare transfers, which in the decentralized equilibrium equates labor force allocations and the growth rate of knowledge to their socially optimal counterparts.

the relation between NL_x and L_Y (1.32), returns on knowledge accumulation (1.31), and the relation between NL_x and NL_r (1.37):

$$NL_x = \frac{1}{1-\tau_x}\frac{\sigma}{1-\sigma}b^k L_Y, \tag{1.90}$$

$$g_{q_\lambda} = r - g_\lambda\left(\frac{L_x}{L_r} + 1 + \alpha\frac{N-1}{N}\frac{\tau_\lambda}{1-\tau_\lambda}\right), \tag{1.91}$$

$$NL_x = D^{GO}\left(L - NL_r\right), \tag{1.92}$$

where D^{GO} is the counterpart of D^k,

$$D^{GO} = \left[\left(1-\tau_x\right)\frac{1-\sigma}{\sigma}\frac{1}{b^k} + 1\right]^{-1},$$

and I use GO to denote the decentralized equilibrium with government.

Proposition 14. *Let the marginal tax rates be constant. In such a case, labor force allocations and the growth rate of knowledge g_λ are*

$$NL_r = \frac{1}{\xi}\frac{\xi D^{GO}L - \rho}{\xi\left(\theta-1\right)\left(\sigma+\mu\right) + D^{GO} - \alpha\frac{N-1}{N}\frac{\tau_\lambda}{1-\tau_\lambda}},$$

$$NL_x = D^{GO}\frac{\left[\left(\theta-1\right)\left(\sigma+\mu\right) - \alpha\frac{N-1}{N}\frac{\tau_\lambda}{1-\tau_\lambda}\right]L + \frac{1}{\xi}\rho}{\left(\theta-1\right)\left(\sigma+\mu\right) + D^{GO} - \alpha\frac{N-1}{N}\frac{\tau_\lambda}{1-\tau_\lambda}},$$

$$L_Y = \left(1-\tau_x\right)\frac{1-\sigma}{\sigma b^k}NL_x,$$

$$g_\lambda = \xi NL_r.$$

Proof. See Proofs Appendix. □

Therefore, in order to have the socially optimal growth rate and allocations, it is sufficient to have

$$NL_r = NL_r^{SP}, NL_x = NL_x^{SP}.$$

To achieve such an outcome, it is sufficient to subsidize the purchases of high-tech goods,

$$\tau_\lambda = 0, \tag{1.93}$$

$$\tau_x = \frac{e^k\mu + \sigma}{e^k\left(\sigma+\mu\right)}, \tag{1.94}$$

where τ_x equates D^{GO} to D^{SP}. It is enough to subsidize the demand for high-tech goods because the returns on knowledge accumulation are fully appropriated (i.e.,

$I^1_{S.2-3} = 0$).[28]

Although under this policy labor force allocations and the growth rate of knowledge in the decentralized equilibrium are equal to their socially optimal counterparts, welfare is not because in the decentralized equilibrium there is a lower number of high-tech firms/goods. The policy instrument that can correct for this is T_π. It is straightforward to show that it is sufficient to set

$$T_\pi = wL_x\tau_\pi, \tag{1.95}$$

where τ_π is such that for any finite N, the profits of high-tech firms are greater than zero, but for $N = +\infty$, profits are zero.

Corollary 10. *Rate τ_π can be derived from a zero profit condition and is given by*

$$\begin{aligned}\tau_\pi = & \frac{\varepsilon - 1 + D^{SP}}{(\varepsilon - 1)\left[(\theta - 1)(\sigma + \mu)\xi D^{SP} L + D^{SP}\right]} \\ & \times \left[\frac{\varepsilon - 1 - (\theta - 1)(\sigma + \mu)}{\varepsilon - 1 + D^{SP}}\xi D^{SP} L - \rho\right].\end{aligned} \tag{1.96}$$

Proof. See Proofs Appendix. □

The second line of (1.96) needs to be positive in order to have $N > 1$ in (1.83). Therefore, τ_π is greater than zero implying that entry into high-tech industry needs to be subsidized. Such subsidies are in the spirit of the R&D subsidies in the Romer (1990) model to the extent that entry can be thought to be a result of R&D that generates new types of high-tech goods.[29]

The result that τ_π is greater than zero is not stemming from the cost-free entry assumption. The next section shows that even if entry into high-tech industry entailed positive costs, then it still could be that at least in the very long-run the Social Planner sets $N = +\infty$, whereas in a decentralized equilibrium, the market is saturated for $N < +\infty$. The Social Planner can prefer to have $N = +\infty$ because as λ grows, the marginal product of N increases.

Entry Regime 3: Costly Entry

In this section, I assume that entry into the high-tech industry entails endogenous costs. I focus on cases where there is an exchange of knowledge among high-tech firms.

[28] Appendix E.7 offers a policy which subsidizes the production of high-tech goods and R&D expenditures. It shows that the subsidy rates for these expenditures should be equal in order to have first-best allocations and growth rates because in a high-tech firm, the allocations of labor to production and R&D are affected by relative price distortions equally.

[29] Appendix E.4 shows how τ_λ can be used together with τ_x when high-tech firms do not take the price of knowledge as exogenous. If $\tau_\lambda \neq 0$, then subsidy rate τ_π is not given by (1.96).

Further, I do not assume that parameters are such that CME necessarily crosses ZP. This restriction can be lifted since when entry entails endogenous costs, positive profits can be allowed.

Firm Entry

In order to enter into the high-tech industry and to generate its distinct type of high-tech good, the potential producer has to invest. The investment is in terms of final goods. The entrant should borrow the resources for the investment from the household at the market interest rate r.

The creation of the distinct type of high-tech good is given by

$$\dot{N} = \eta S, \ \ \eta \geq 0, \tag{1.97}$$

where $\dot{N}$ is the new high-tech good created by the investment S, and η is the efficiency of investments.

The entrants are assumed to break-even on a zero net-value constraint,

$$V\dot{N} = S. \tag{1.98}$$

From this expression, (1.2), (1.6), (1.9), (1.10), (1.18), (1.98), and the Hamilton-Jacobi-Bellman equation $\dot{V} = rV - \pi$, it follows that for $\eta \in (0, +\infty)$

$$Y = C + S, \tag{1.99}$$

given that the assets in this economy are the high-tech firms ($A = VN$.) Meanwhile, in terms of previously analyzed cases of entry, $\eta = 0$ in (1.97) corresponds to when there are exogenous barriers to entry. In such a case, (1.98) does not bind. The limiting case $\eta = +\infty$ corresponds to cost-free endogenous entry. In such a case, any infinitesimally small investment leads to entry. Given that this investment is a cost, the entrants would select to invest 0 and enter. Therefore, in both limiting cases $\eta = 0$ and $\eta = +\infty$, (1.39) holds.

Hereafter, I assume that η is a small number ($\eta \approx 0$). Under such a restriction there is no transition in the hypothetical Social Planner's solution.

Decentralized Equilibrium

It is instructive to derive the profit function of a high-tech firm first. As in the case when entry entails no cost, it can be written as

$$\pi = wL_x\bar{\pi},$$

where

$$\bar{\pi} = \frac{1}{e^k - 1} - \frac{g_\lambda}{r - \left(g_w - I^0_{\dot{N}=0} g_N\right)}, \ k = CR, BR, \tag{1.100}$$

and

$$I^0_{\dot{N}=0} = \begin{cases} 1 \ for \ \dot{N} \neq 0, \\ 0 \ otherwise. \end{cases}$$

Corollary 11. *$\bar{\pi}$ in (1.100) is a monotonically decreasing function of N.*

Proof. See Proofs Appendix. □

The competition intensifies with the number of firms N. When strategic interactions in the product market are non-negligible, the intensity of competition and profits are related negatively. The negative relation between N and $\bar{\pi}$ reflects exactly this point.

Hereafter, I focus only on a balanced growth path analysis. Depending on the household's preferences, final goods production technology, and the high-tech firm's knowledge accumulation process, there are two cases when the economy grows at constant rates. In the first case, there are so many high-tech firms that the new entrant's impact on others' demand is negligible, while in the second case, the next entrant will have negative profit streams (i.e., there are endogenous barriers to entry).[30]

In the first case, the counterpart of CME in (1.46) is always lower than the counterpart of ZP in (1.70). On the balanced growth path there are infinitely many high-tech firms, and there is permanent entry ($N = +\infty$, $\dot{N} > 0$).

Proposition 15. *The growth rates of final output and knowledge are*

$$\begin{aligned} g_Y^{CE} &= B g_\lambda^{CE}, \\ g_\lambda^{CE} &= \frac{\xi DL - \rho}{\left(\theta - 1 + I^0_{\dot{N}=0}\right) B + \alpha I^1_{S.2-3} + D}, \end{aligned} \tag{1.101}$$

where I use superscript CE– costly entry –in order to distinguish the outcomes of this setup from the previous setups and

$$B = \frac{(\varepsilon - 1)(\sigma + \mu)}{\varepsilon - 1 - I^0_{\dot{N}=0} (\sigma + \mu)}.$$

Proof. See Proofs Appendix. □

Labor force allocations in this case can be derived from (1.30), (1.36), and (1.37). In the denominator of g_λ^{CE} (1.101) $I^0_{\dot{N}=0}$ captures the effect of continuous entry into

[30] This ordering is possible given that $\bar{\pi}$ in (1.100) is negatively related to the number of firms, and the investments in knowledge accumulation are fixed costs.

the high-tech industry on innovation incentives of high-tech firms. Continuous entry erodes the returns on innovation. *Ceteris paribus* this leads to lower investments in R&D.

In the second case, let N^{**} $(< +\infty)$ be the last high-tech firm that will have non-negative profit streams if it enters. There is no entry after N^{**} (i.e., $\dot{N} = 0$) because for any $N > N^{**}$, the value V would be negative.[31] When there is no entry, the economy is on a balanced growth path; therefore, N^{**} is determined from the intersection of CME and ZP curves. In such a case, labor force allocations, growth rates, and the number of firms under different types of competition can be obtained from (1.42)-(1.46) and (1.71).[32]

Social Optimum

The hypothetical Social Planner's problem is given by (1.50)-(1.52) and (1.97). I assume that the Social Planner can make negative investments in the high-tech industry (i.e., in N), and η is close to zero. Under these assumptions there is no transition in the social optimum.

Proposition 16. *The socially optimal growth rates of final output and knowledge are given by*

$$g_Y^{CE,SP} = B^{SP} g_\lambda^{CE,SP}, \tag{1.102}$$

$$g_\lambda^{CE,SP} = \frac{\xi D^{SP} L - \rho}{(\theta - 1) B^S + D^{SP}}, \tag{1.103}$$

where

$$B^{SP} = \frac{(\varepsilon - 1)(\sigma + \mu)}{\varepsilon - 1 - (\sigma + \mu)}.$$

Proof. See Proofs Appendix. □

In turn, the socially optimal labor force allocations can be found from (1.36), (1.53), and (1.57).

Corollary 12. *There is permanent entry in the social optimum.*

[31] Strictly speaking, the firm that has zero profits invests zero; therefore, according to (1.97), it also does not enter. Therefore, N^{**} is an upper bound for the number of firms in high-tech industry. However, since $\bar{\pi}$ in (1.100) is a continuous function of the number of firms, N^{**} is exactly the number of firms in the industry.

[32] When there is no exchange of knowledge and the counterpart of ZP crosses the counterpart of CME from above at finite N, then the balanced growth path properties of the model are summarized in the section Entry Regime 2. However, if ZP does not cross CME on a balanced growth path the economy needs to be static when B is finite and positive.

The permanent entry result is due to the absence of market incentives in the social optimum. It stands in contrast to the decentralized equilibrium result, where it may be the case that there are endogenous barriers to entry. It holds because the accumulation of knowledge (R&D) increases the marginal product of N.

Comparisons and Policy Inference

It is straightforward to show that in both cases when there are endogenous barriers to entry in the decentralized equilibrium ($\dot{N} = 0$) and there are no barriers to entry ($\dot{N} > 0$), the following relationships hold:

$$g_{\lambda}^{CE,SP} > g_{\lambda}^{CE,S.1} > g_{\lambda}^{CE,S.2}.$$

Further, similar to the previous sections, it is straightforward to show that in both cases when $\dot{N} = 0$ and $\dot{N} > 0$ in the decentralized equilibrium, the economy fails to have socially optimal labor force allocations. From (1.102) and (1.103), it also follows that in the social optimum, the growth rate of the final output is higher if there is continuous entry compared to when there is no continuous entry.

Corollary 13. *If there is continuous entry into the high-tech industry ($\dot{N} > 0$) and knowledge licensing among high-tech firms, then the following policy delivers socially optimal allocations and growth rates as a decentralized equilibrium outcome.*

$$\tau_x = \frac{e^k \mu + \sigma}{e^k (\sigma + \mu)},$$
$$\tau_\lambda = \frac{\frac{N}{N-1}\frac{1}{\alpha}B}{1 + \frac{N}{N-1}\frac{1}{\alpha}B}.$$

Proof. See Proofs Appendix. □

In this policy, τ_x is the same as in (1.94) and subsidizes the purchases of final goods. In contrast, τ_λ in this policy is greater than zero, which means that this policy also subsidizes knowledge licensing. It does so in order to motivate R&D in the high-tech industry and alleviate the negative effect of continuous entry on the innovation incentives of high-tech firms.

Continuous entry, in turn, can be guaranteed with lump-sum transfers to high-tech firms (1.95), which make the profits of these firms marginally greater than zero for any N.

Discussion of Implemented Policies

Many recently implemented policies, for example the Telecommunications Act of 1996, have a structure which is similar to the suggested optimal policies. The similarities are that these policies promote demand for high-tech goods (e.g., telecommunications goods/services) and as market regulation they motivate entry. Despite these similarities, these policies seem to lack important components. For example, the Telecommunications Act of 1996 overlooks the incentive of telecommunications firms to under-invest in R&D and the negative effect of entry on the rate of return on that investment.[33] It also does not incorporate transfers, which could allow permanent/continuous entry if needed.

1.4 Conclusions

The model presented in this paper incorporates knowledge (patent) licensing into a stylized endogenous growth framework, where the engine of growth is high-tech firms' in-house R&D. The inference from this model suggests that if there is knowledge licensing, high-tech firms innovate more, and economic growth is higher than in cases where there are knowledge spillovers and/or no knowledge exchange among these firms. The results also suggest that innovation in the high-tech industry and economic growth increase with the intensity and toughness of competition in that industry. Such an inference holds also for the number of high-tech firms if there is an exchange of knowledge among these firms in the form of licensing or spillovers. Increasing the number of high-tech firms increases innovation in the high-tech industry and the growth rate of the economy. However, if there is no exchange of knowledge among high-tech firms, then increasing the number of firms can also discourage innovation and reduce economic growth.

Innovation in the high-tech industry declines with the magnitude of externalities that stem from the use of high-tech goods. However, the rate of economic growth increases with it. Further, the existence of such externalities creates a wedge between resource allocations in a decentralized equilibrium and socially optimal allocations. In this model, this implies that the existence of externalities also creates a wedge between growth rates in a decentralized equilibrium and the socially optimal growth rate.

If entry (or exit) is endogenous and entails no costs, innovation in the industry and economic growth are again higher when there is knowledge licensing. However, this

[33] It has to be acknowledged that, for instance, the Federal Communications Commission (FCC) in the United States envisions the need to foster innovation in the telecommunications industry (see, for instance, FCC, 2008). However, the FCC tries to foster innovation by means of having more competition in the telecommunications industry by motivating free entry.

happens at the expense of a lower number of high-tech firms. More intensive and/or tougher competition reduce the number of high-tech firms. If there is an exchange of knowledge among these firms, the intensity and toughness of competition do not affect, however, allocations, innovation, and economic growth. In contrast, allocations change and innovation and economic growth tend to increase with the intensity and toughness of competition if there is no exchange of knowledge among high-tech firms.

If entry entails no costs, a policy consisting of four instruments can be sufficient for achieving the first-best outcome in a decentralized equilibrium. The policy gives the bargaining power in the market for knowledge to the licensors so that they appropriate all the benefit. Further, it subsidizes the purchases of high-tech goods so that it offsets the negative effect of price setting by high-tech firms and takes into account the externalities from the use of high-tech goods. Finally, it subsidizes entry into the high-tech industry and uses lump-sum taxes to cover all these subsidies.

Meanwhile, if entry entails endogenous costs, then in the social optimum, there is continuous entry into the high-tech industry. In a decentralized equilibrium, continuous entry erodes the returns on innovation and therefore reduces the R&D effort of high-tech firms. In order to alleviate this effect and achieve first best outcomes in a decentralized equilibrium, the policy also needs to subsidize knowledge licensing.

Appendix

Proofs Appendix

Proof of Proposition 1: The growth rates of quantities and prices that characterize the essential dynamics of this model can be obtained from (1.3)-(1.10), (1.11), (1.19), and (1.20). These growth rates are

$$g_C = \frac{1}{\theta}(r-\rho), \tag{1.104}$$

$$g_Y = (\sigma+\mu) g_X + (1-\sigma) g_{L_Y}, \tag{1.105}$$

$$g_X = \frac{\varepsilon}{\varepsilon-1} g_N + g_x, \tag{1.106}$$

$$g_Y = g_w + g_{L_Y}, \tag{1.107}$$

$$g_x = g_\lambda + g_{L_x}, \tag{1.108}$$

$$g_w = g_{q_\lambda} + g_N + g_\lambda. \tag{1.109}$$

Combining (1.31) with (1.19), (1.20), (1.30), (1.32), (1.36), (1.37), (1.40), and (1.104)-(1.109) gives a differential equation in L_r,

$$\begin{aligned} \dot{L}_r = & \frac{L - NL_r}{N\left[(1+\mu)(\theta-1)+1\right]} \\ & \times \left\{ \left[(\theta-1)(\sigma+\mu) + \alpha I^1_{S.2-3} + D^k\right] \xi I^N_{S.1-2} L_r - \left(\xi D^k \frac{I^N_{S.1-2}}{N} L - \rho\right) \right\}, \end{aligned} \tag{1.110}$$

for all S.1-3 cases.

Let parameter restriction (1.41) hold. The first term of the differential equation (1.110) is non-negative. Without that term, the characteristic root of the differential equation is positive, $\frac{\partial \dot{L}_r}{\partial L_r} > 0$. This, together with the neoclassical production function of final goods (3.1), implies that there is a unique L_r such that (1.110) is stable and $NL_r, NL_x, L_Y \in (0, L)$,

$$L_r^{NE} = \frac{1}{\xi I^N_{S.1-2}} \frac{\xi D^k \frac{I^N_{S.1-2}}{N} L - \rho}{(\theta-1)(\sigma+\mu) + \alpha I^1_{S.2-3} + D^k}. \tag{1.111}$$

Combining this expression with the relations between NL_x and L_Y (1.32) and NL_x and NL_r (1.37) gives the equilibrium allocations of labor force (1.42)-(1.44). Given that allocations of the labor force are constant from (1.40), (1.105), and (1.108), it follows that

$$g_C^{NE} = g_Y^{NE} = g_w^{NE} = (\sigma+\mu) g_X^{NE},$$

$$g_X^{NE} = g_x^{NE} = g_\lambda^{NE},$$

where g_λ is given by (1.30),

$$g_\lambda^{NE} = \frac{\xi D^k \frac{I_{S.1-2}^N}{N} L - \rho}{(\theta - 1)(\sigma + \mu) + \alpha I_{S.2-3}^1 + D^k}.$$

Therefore, in a decentralized equilibrium with no entry, if (1.41) holds, the economy makes a discrete "jump" to a balanced growth path in all S.1-3 cases.

Proof of Proposition 2: The value of a high-tech firm if high-tech firms innovate [i.e., $NL_r \in (0, L)$] is

$$V^{NL_r \in (0,L)} = \frac{1}{(\theta - 1)(\sigma + \mu) g_\lambda + \rho} \pi(t) \exp\left[-(\sigma + \mu) g_\lambda t\right],$$

where I have dropped the superscript NE, and $\pi(t)$ can be derived from (3.1), (1.5), (1.9), (1.10), (1.11), (1.18), (1.19), (1.42) and (1.43),

$$\begin{aligned} \pi(t) = & \frac{1}{N} \sigma \left(N^{\frac{1}{\varepsilon - 1}} \lambda(0) NL_x \right)^{\sigma + \mu} L_Y^{1-\sigma} \frac{1}{e^k} \exp\left[(\sigma + \mu) g_\lambda t\right] \\ & \times \left\{ 1 - \frac{e^k - 1}{D^k} \frac{\xi D^k \frac{I_{S.1-2}^N}{N} L - \rho}{\left[(\theta - 1)(\sigma + \mu) + \alpha I_{S.2-3}^1\right] \xi \frac{I_{S.1-2}^N}{N} L + \rho} \right\}. \end{aligned}$$

In turn, if none of the high-tech firms innovate then the economy is static ($g_Y = g_\lambda = 0$), and each high-tech firm's profits and value are given by

$$\begin{aligned} \pi &= \frac{1}{N} \sigma \left(N^{\frac{\varepsilon}{\varepsilon - 1}} \lambda(0) L_x \right)^{\sigma + \mu} L_Y^{1-\sigma} \frac{1}{e^k}, \\ V^{NL_r = 0} &= \frac{1}{N} \sigma \left(N^{\frac{\varepsilon}{\varepsilon - 1}} \lambda(0) L_x \right)^{\sigma + \mu} L_Y^{1-\sigma} \frac{1}{e^k} \frac{1}{\rho}. \end{aligned}$$

It can be easily shown that

$$V^{NL_r \in (0,L)} < V^{NL_r = 0},$$

which means that the value of any high-tech firm is higher if none of the high-tech firms engage in R&D.

Proof of Proposition 3: Using (1.54), the expression for the returns on knowledge accumulation (1.56) can be re-written as

$$g_{q_\lambda} = \rho - \left(\frac{1-\sigma}{1+\mu} \xi I^N_{S.1-2} L_r + \xi D^{SP} \frac{I^N_{S.1-2}}{N} L \right). \tag{1.112}$$

Meanwhile, from (1.51)-(1.54) and (1.57), it follows that

$$g_{L_x} = g_{L_Y} = -\frac{N\dot{L}_r}{L - NL_r}, \tag{1.113}$$

$$g_C = (\sigma + \mu)(g_\lambda + g_{L_x}) + (1-\sigma) g_{L_x}, \tag{1.114}$$

$$g_\lambda = \xi I^N_{S.1-2} L_r, \tag{1.115}$$

$$g_{q_\lambda} = -g_\lambda - g_{L_x} - (\theta - 1) g_C. \tag{1.116}$$

Combining (1.112)-(1.116) gives a differential equation in L_r,

$$\dot{L}_r = \frac{L - NL_r}{N[(\theta-1)(1+\mu)+1]} \times \left\{ \left[(\theta-1)(\sigma+\mu) + D^{SP}\right] \xi I^N_{S.1-2} L_r - \left(\xi D^{SP} \frac{I^N_{S.1-2}}{N} L - \rho \right) \right\}. \tag{1.117}$$

Without the first non-negative term, this expression implies that $\frac{\partial \dot{L}_r}{\partial L_r} > 0$. Therefore, there is a unique L_r such that (1.117) is stable, and $NL_r \in (0, L)$,

$$L_r^{NE,SP} = \frac{1}{\xi I^N_{S.1-2}} \frac{\xi D^{SP} \frac{I^N_{S.1-2}}{N} L - \rho}{(\theta-1)(\sigma+\mu) + D^{SP}}. \tag{1.118}$$

The numerator in (1.118) is positive if (1.58) is positive.

Combining (1.118) with (1.53) and (1.57) gives the socially optimal (interior) allocations of the labor force (1.59)-(1.61).

Given that labor force allocations are constant from (1.39) and (1.114), it follows that

$$g_Y^{NE,SP} = (\sigma + \mu) g_\lambda^{NE,SP},$$

where $g_\lambda^{NE,SP}$ can be derived from (1.52) and (1.118),

$$g_\lambda^{NE,SP} = \frac{\xi D^{SP} \frac{I^N_{S.1-2}}{N} L - \rho}{(\theta-1)(\sigma+\mu) + D^{SP}}.$$

Therefore, the Social Planner chooses allocations such that the economy, where there is "no entry", makes a discrete jump to a balanced growth path.

Proof of Proposition 4: The lifetime utility of the representative household when the Social Planner innovates is

$$U^{NE,SP,NL_r\in(0,L)} \equiv U = -\frac{1}{\theta-1}\frac{1}{(\sigma+\mu)(\theta-1)g_\lambda^{NE,SP}+\rho}\times$$
$$\left[\left(N^{\frac{1}{\varepsilon-1}}\lambda(0)NL_x^{NE,SP}\right)^{\sigma+\mu}\left(L_Y^{NE,SP}\right)^{1-\sigma}\right]^{1-\theta}+\frac{1}{\rho}\frac{1}{\theta-1},$$

where $NL_x^{NE,SP}$, $L_Y^{NE,SP}$, and $g_\lambda^{NE,SP}$ are given by (1.60), (1.61), and (1.63). When the Social Planner does not innovate it is

$$U^{NE,SP,NL_r=0} \equiv U == \frac{1}{\theta-1}\frac{1}{\rho}\left[\left(N^{\frac{1}{\varepsilon-1}}\lambda(0)NL_x^{NE,SP}\right)^{\sigma+\mu}\left(L_Y^{NE,SP}\right)^{1-\sigma}\right]^{1-\theta}+\frac{1}{\rho}\frac{1}{\theta-1},$$

where $NL_x^{NE,SP}$ and $L_Y^{NE,SP}$ are given by (1.65) and (1.66).

Using (1.60), (1.61), (1.63), (1.65) and (1.66), it can be shown that the inequality of

$$U^{NE,SP,NL_r=0} \leq U^{NE,SP,NL_r\in(0,L)}$$

is equivalent to

$$\left(\xi D^{SP}\frac{I^N_{S.1-2}}{N}L\frac{1}{\rho}\right)^{(\theta-1)(1+\mu)} \leq \left[\frac{(\theta-1)(1+\mu)\xi D^{SP}\frac{I^N_{S.1-2}}{N}L\frac{1}{\rho}+1}{(\theta-1)(1+\mu)+1}\right]^{(\theta-1)(1+\mu)+1}.$$

Denote

$$z=\xi D^{SP}\frac{I^N_{S.1-2}}{N}L\frac{1}{\rho}$$

and take the natural logarithm of both sides of this inequality:

$$0\leq[(\theta-1)(1+\mu)+1]\left[\ln((\theta-1)(1+\mu)z+1)-\ln((\theta-1)(1+\mu)+1)\right]$$
$$-(\theta-1)(1+\mu)\ln z.$$

The derivative of the right-hand side of this inequality with respect to z is greater than zero. Meanwhile, the right-hand side is equal to zero when $z=1$. Therefore, given that (1.58) holds, $z>1$, and

$$U^{NE,SP,NL_r=0} \leq U^{NE,SP,NL_r\in(0,L)}.$$

Proof of Proposition 9: It is straightforward to show that if the number of firms N is fixed, the economy is on a balanced growth path. Further, it is straightforward to show that $\bar{\pi}$ in (1.68) declines with N (see also Corollary 11). This, together with a cost-free entry and that $\bar{\pi}$ in (1.68) is a constant on the balanced growth path, implies that at time zero ($t = 0$), N makes a discrete jump to the balanced growth path equilibrium level, where $\bar{\pi} = 0$. Thereafter in a decentralized equilibrium with cost-free entry, the economy is always on a balanced growth path.

Proof of Proposition 11: If (1.82) and the remaining optimal rules/constraints are binding, then when there is no exchange of knowledge ($I^N_{S.1-2} = 1$), it is straightforward to show that the optimal labor force allocations are

$$NL_r^{CFE,SP,S.3} = \frac{\sigma + \mu}{\varepsilon(1+\mu) - (1-\sigma)} L, \tag{1.119}$$

$$NL_x^{CFE,SP,S.3} = \frac{(\varepsilon - 1)(\sigma + \mu)}{\varepsilon(1+\mu) - (1-\sigma)} L, \tag{1.120}$$

and

$$L_Y^{CFE,SP,S.3} = \frac{(\varepsilon - 1)(1 - \sigma)}{\varepsilon(1+\mu) - (1-\sigma)} L. \tag{1.121}$$

It can be further shown that the returns on knowledge accumulation are given by

$$g_{q_\lambda} = \rho - \xi \frac{I^N_{S.1-2}}{N} \frac{\varepsilon(\sigma + \mu)}{\varepsilon(1+\mu) - (1-\sigma)} L. \tag{1.122}$$

In turn, from (1.51), (1.52), (1.82) and (1.119)-(1.121), it follows that

$$g_{L_Y} = g_{NL_x} = g_{NL_r} = 0, \tag{1.123}$$

$$g_C = (\sigma + \mu)\left(\frac{1}{\varepsilon - 1} g_N + g_\lambda\right), \tag{1.124}$$

$$g_\lambda = \xi L_r, \tag{1.125}$$

$$g_{q_\lambda} = -g_\lambda - (\theta - 1) g_C + g_N. \tag{1.126}$$

Combining these conditions with (1.122) gives a differential equation in N,

$$g_N = -\frac{\varepsilon - 1}{\varepsilon - 1 - (\theta - 1)(\sigma + \mu)} \times \left[\xi(\sigma + \mu) \frac{\varepsilon - 1 - (\theta - 1)(\sigma + \mu)}{\varepsilon(1+\mu) - (1-\sigma)} L \frac{1}{N} - \rho\right].$$

Since $\frac{\partial g_N}{\partial N} > 0$, the only stable solution is (1.83):

$$N = \frac{\xi(\sigma + \mu)}{\rho} \frac{\varepsilon - 1 - (\theta - 1)(\sigma + \mu)}{\varepsilon(1+\mu) - (1-\sigma)} L,$$

which implies that

$$g_N = 0.$$

Therefore from (1.52) and (1.119), it follows that (1.84) holds:

$$g_\lambda^{CFE,SP,S.3} = \frac{\rho}{\varepsilon - 1 - (\theta - 1)(\sigma + \mu)}.$$

This implies that the economy needs to make a discrete jump to a balanced growth path at time zero.

Proof of Proposition 12: In order to check whether (1.82) is binding, denote

$$\bar{U}^{CFE,SP,S.3,N<+\infty} = U^{CFE,SP,S.3,N<+\infty} - \frac{1}{\rho}\frac{1}{\theta - 1}.$$

From (1.51), it follows that

$$\bar{U}^{CFE,SP,S.3,N<+\infty} = -\frac{1}{\theta - 1}\frac{1}{(\theta - 1)(\sigma + \mu) g_\lambda^{SP} + \rho} \times \left[\left(N^{\frac{1}{\varepsilon - 1}} \lambda(0) NL_x\right)^{\sigma + \mu} L_Y^{1-\sigma}\right]^{1-\theta},$$

where N, g_λ^{SP}, NL_x, and L_Y are given by (1.83), (1.84), (1.120), and (1.121) correspondingly.

When $\theta > 1$

$$\bar{U}^{CFE,SP,S.3,N=+\infty} = 0,$$

whereas

$$\bar{U}^{CFE,SP,S.3,N<+\infty} \leq 0.$$

Meanwhile, when $\theta = 1$,

$$\bar{U}^{CFE,SP,S.3,N=+\infty} = +\infty,$$

whereas

$$\bar{U}^{CFE,SP,S.3,N<+\infty} < +\infty.$$

Clearly, therefore,

$$\bar{U}^{CFE,SP,S.3,N=+\infty} > \bar{U}^{CFE,SP,S.3,N<+\infty},$$

implying that the solution with finite N is not optimal.

Therefore, when there is no exchange of knowledge ($I_{S.1-2}^N = 1$), the Social Planner sets

$$N = +\infty,$$

$$g_\lambda^{CFE,SP,S.3} = NL_r^{CFE,SP,S.3} = 0,$$
$$NL_x^{CFE,SP,S.3} = D^{SP}L,$$
$$L_Y^{CFE,SP,S.3} = \frac{1-\sigma}{\sigma+\mu}D^{SP}L,$$

and the economy is static.

Proof of Proposition 13: If there is an exchange of knowledge among high-tech firms, the expression for perceived elasticity of substitution e^k (1.71) indicates that e^k does not depend on the type of competition. Since for any given number of firms the perceived elasticity of substitution is higher under Bertrand competition ($e^{BR} > e^{CR}$), from (1.71), it follows that in equilibrium there are fewer high-tech firms under Bertrand competition than under Cournot competition. Further, given that perceived elasticities of substitution monotonically increase with the number of firms and the actual elasticity of substitution, from (1.71), it follows that under both types of competition the number of firms declines with ε and increases with μ. It also increases with α if there are knowledge spillovers (S.2) and does not depend on α if there is knowledge licensing (S.1).

If there is no exchange of knowledge among high-tech firms, the right-hand side of (1.76) and the perceived elasticity of substitution e^k from (1.34) and (1.35) increase in N and $e^{BR} > e^{CR}$ for any N. Therefore, also in this case, there are more firms under Cournot competition than under Bertrand competition.[34] Moreover, the number of firms N declines with ε and increases with μ and α.

Proof of Proposition 14: Let the marginal tax rates be constant. This implies that (1.104)-(1.109) hold. Combining (1.91), (1.92), and (1.104)-(1.109) gives the counterpart of (1.110),

$$\dot{L}_r = \frac{L - NL_r}{N\left[(1+\mu)(\theta-1)+1\right]} \times \left\{\left[(\theta-1)(\sigma+\mu) + D^{GO} - \alpha\frac{N-1}{N}\frac{\tau_\lambda}{1-\tau_\lambda}\right]\xi NL_r - \left(\xi D^{GO}L - \rho\right)\right\}.$$

The stationary solution of this differential equation is given by

$$L_r = \frac{1}{\xi N}\frac{\xi D^{GO}L - \rho}{(\theta-1)(\sigma+\mu) + D^{GO} - \alpha\frac{N-1}{N}\frac{\tau_\lambda}{1-\tau_\lambda}}.$$

[34] It can be shown also that the quadratic polynomial in (1.76) opens upward, and under Bertrand competition for any N, it is lower than under Cournot competition. Since a stable equilibrium corresponds to the smaller roots of the polynomials, the number of firms is lower under Bertrand competition.

The remaining labor force allocations can be derived from (1.90) and (1.92).

Proof of Corollary 10: Subsidy/tax rate τ_π can be derived from the zero profit condition

$$\pi = 0 \Leftrightarrow \tau_\pi = \frac{L_r}{L_x} - \frac{1}{\varepsilon - 1},$$

where

$$\frac{L_r}{L_x} = \frac{L_r^{SP}}{L_x^{SP}} = \frac{\xi D^{SP} L - \rho}{(\theta - 1)(\sigma + \mu)\xi D^{SP} L + D^{SP}\rho}.$$

Proof of Corollary 11: To prove that $\bar{\pi}$ is monotonically decreasing in N, consider its first term. It can be shown that

$$\frac{\partial e^k}{\partial N} > 0 \;\; k = CR, BR.$$

This implies that the first term is a monotonically decreasing function of N. For the second term

$$\frac{\partial}{\partial N}\frac{g_\lambda}{r - (g_w - \delta g_N)} = \frac{\frac{NL_x}{L_Y}\left(\frac{\partial}{\partial N}\frac{NL_r}{L_Y}\right) - \frac{NL_r}{L_Y}\left(\frac{\partial}{\partial N}\frac{NL_x}{L_Y}\right)}{\left(\frac{NL_x}{L_Y}\right)^2},$$

where

$$\frac{\partial}{\partial N}\frac{NL_r}{L_Y} = \frac{1}{b}\left(\frac{NL_r + L_Y}{L_Y}\right)\frac{\partial b}{\partial N},$$
$$\frac{\partial}{\partial N}\frac{NL_x}{L_Y} = \frac{1}{b}\frac{NL_x}{L_Y}\frac{\partial b}{\partial N}.$$

Therefore,

$$-\frac{\partial}{\partial N}\frac{g_\lambda}{r - (g_w - \delta g_N)} = -\left(\frac{1}{b^k}\right)^2 \frac{1-\sigma}{\sigma}\frac{\partial b^k}{\partial N},$$

where

$$\frac{\partial b^k}{\partial N} > 0.$$

Therefore, the second term is a monotonically decreasing function of the number of firms as well. Hence, $\bar{\pi}$ is a monotonically decreasing function of N.

An alternative proof for $\bar{\pi}' < 0$ uses the labor market clearing condition (1.36), final and telecom goods production functions (3.1) and (1.11), and the relation between labor demand in final goods and high-tech goods production. A sufficient condition to observe the desired relationship is $b\sigma L\frac{1-\sigma}{1+\mu} < NL_x$, which can be shown to hold from the labor market clearing condition.

Proof of Proposition 15: The growth rates and labor force allocations can be derived from (1.30)-(1.38) and (1.104)-(1.109). When there is continuous entry into the high-tech industry, the growth rate of knowledge is

$$g_{\lambda}^{CE} = \frac{\xi DL - \rho}{\left(\theta - 1 + I_{\dot{N}=0}^{0}\right) B + \alpha I_{S.2-3}^{1} + D}. \tag{1.127}$$

The growth rate of consumption, final output, the number of firms and savings are

$$g_{C}^{CE} = g_{Y}^{CE} = g_{N}^{CE} = g_{S}^{CE} = B g_{\lambda}^{CE}.$$

Proof of Proposition 16: Given that in this case N is an endogenous state variable, it is convenient to re-write labor force allocations to knowledge accumulation and the production of high-tech goods as

$$\bar{L}_r = N L_r,$$
$$\bar{L}_x = N L_x.$$

The hypothetical Social Planner then solves:

$$\max_{S,\bar{L}_x,\bar{L}_r} U = \int_0^{+\infty} \frac{C_t^{1-\theta} - 1}{1-\theta} \exp(-\rho t)\, dt.$$

$s.t.$

$$Y = C + S, \tag{1.128}$$

$$Y = \left(N^{\frac{1}{\varepsilon-1}} \lambda \bar{L}_x\right)^{\sigma+\mu} \left(L - \bar{L}_x - \bar{L}_r\right)^{1-\sigma}, \tag{1.129}$$

$$\dot{\lambda} = \xi \lambda \bar{L}_r, \tag{1.130}$$

$$\dot{N} = \eta S, \tag{1.131}$$

$$\lambda(0) > 0, N(0) > 1 - given.$$

The Social Planner's optimal choice for the accumulation of N is given by

$$[N] : \dot{q}_N = q_N \rho - \frac{\sigma + \mu}{\varepsilon - 1} Y \frac{1}{N} C^{-\theta}. \tag{1.132}$$

The remaining optimal rules are as follows:

$$\left[\bar{L}_x\right] : \bar{L}_x = \frac{\sigma + \mu}{1 - \sigma} L_Y, \tag{1.133}$$

$$\left[\bar{L}_r\right] : q_{\lambda} \xi \lambda = (1 - \sigma) C^{-\theta} \frac{Y}{L_Y}, \tag{1.134}$$

$$[\lambda] : \dot{q}_\lambda = q_\lambda \rho - \left[q_\lambda \xi \bar{L}_r + (\sigma + \mu) C^{-\theta} \frac{Y}{\lambda} \right]. \tag{1.135}$$

Since C and S are in the same terms, it has to be that

$$C^{-\theta} = \eta q_N. \tag{1.136}$$

Using expression (1.134) and the labor market clearing condition (1.36), the returns on knowledge accumulation (1.135) can be re-written as

$$g_{q_\lambda} = \rho - \left(\frac{1-\sigma}{1+\mu} \xi \bar{L}_r + \frac{\sigma+\mu}{1+\mu} \xi L \right). \tag{1.137}$$

In turn, from (1.36) and (1.129)-(1.134), it follows that

$$g_Y = (\sigma + \mu) \left(\frac{1}{\varepsilon - 1} g_N + g_\lambda + g_{\bar{L}_x} \right) + (1 - \sigma) g_{L_Y}, \tag{1.138}$$

$$g_\lambda = \xi \bar{L}_r, \tag{1.139}$$

$$g_N = \eta \frac{S}{N},$$

$$g_{\bar{L}_x} = g_{L_Y} = -\frac{\partial \bar{L}_r}{\partial t} \frac{1}{L - \bar{L}_r},$$

$$g_{q_\lambda} = -\theta g_C + g_Y - g_{L_Y} - g_\lambda. \tag{1.140}$$

From these expressions and (1.132), it is possible to derive a differential equation in L_Y,

$$g_{L_Y} = -\frac{\sigma+\mu}{\mu} \xi L + \xi \frac{\sigma+\mu}{1-\sigma} L_Y + \frac{\sigma+\mu}{(\varepsilon-1)\mu} \eta \frac{C}{N}. \tag{1.141}$$

Since the growth rate of L_Y, increases with L_Y the only stationary solution of this equation is $g_{L_Y} = 0$. This implies that labor force allocations are constant in the social optimum

$$g_{\bar{L}_r} = g_{\bar{L}_x} = g_{L_Y} = 0.$$

Moreover, (1.141) implies a relation between N and λ on a balanced growth path and

$$g_C = g_N.$$

These results, together with (1.128)-(1.132) and (1.135), imply that

$$g_N = const,$$

and

$$g_N = g_S = g_C = g_Y.$$

From (1.138), (1.139), (1.140), and labor market clearing condition (1.36), then it follows that

$$g_Y^{CE,SP} = B^{SP} g_\lambda^{CE,SP},$$
$$g_\lambda^{CE,SP} = \frac{\xi D^{SP} L - \rho}{(\theta - 1) B^{SP} + D^{SP}},$$

and

$$NL_r^{CE,SP} = \frac{1}{\xi} \frac{\xi D^{SP} L - \rho}{(\theta - 1) B^{SP} + D^{SP}}, \tag{1.142}$$
$$NL_x^{CE,SP} = D^{SP} \frac{1}{\xi} \frac{\xi (\theta - 1) B^{SP} L + \rho}{(\theta - 1) B^{SP} + D^{SP}}, \tag{1.143}$$
$$L_Y^{CE,SP} = \frac{1 - \sigma}{\sigma + \mu} D^{SP} \frac{1}{\xi} \frac{\xi (\theta - 1) B^{SP} L + \rho}{(\theta - 1) B^{SP} + D^{SP}}. \tag{1.144}$$

It can be shown that as long as there can be negative investments in N, and η is sufficiently low in the social optimum the economy makes a discrete jump to a balanced growth path at time zero ($t = 0$). This holds because when the economy is relatively abundant in N [(1.144) does not hold], then the Social Planner at time zero selects negative investments in N so that (1.144) holds from the following instance. Meanwhile, sufficiently low η guarantees that the balanced growth path value of N is so low that when the economy is relatively abundant of λ, there are sufficient resources for savings that (immediately) cover the gap between the initial and the balanced growth path value of N. The Social Planner in such a case also selects savings so that the economy makes a discrete jump to a balanced growth path.

Proof of Corollary 13: Let $\dot{N} > 0$ and

$$\tau_x = \frac{e^k \mu + \sigma}{e^k (\sigma + \mu)}$$

so that D^{GO} and D^{SP} are equivalent. Combining equations (1.104)-(1.109) with (1.91) and (1.92) gives the counterpart of (1.110):

$$N\dot{L}_r = \frac{L - NL_r}{\theta B \frac{1+\mu}{\sigma+\mu} + 1} \left[\left(\theta B + D^{SP} - \alpha \frac{N-1}{N} \frac{\tau_\lambda}{1 - \tau_\lambda} \right) \xi N L_r - \left(\xi D^{SP} L - \rho \right) \right].$$

If

$$\alpha \frac{N-1}{N} \frac{\tau_\lambda}{1 - \tau_\lambda} = B,$$

or equivalently

$$\tau_\lambda = \frac{\frac{N}{N-1}\frac{1}{\alpha}B}{1+\frac{N}{N-1}\frac{1}{\alpha}B},$$

then labor force allocations and growth rates in a decentralized equilibrium coincide with the choices of the Social Planner.

Appendix E.1

In this section, I present a setup where high-tech firms cooperate in R&D and select the optimal rules for R&D so as to maximize joint profits. High-tech firms later compete in the product market. I call this case CO - R&D cooperation.[35]

I offer below the setup of the high-tech industry and the optimization problem of high-tech firms in the stage of R&D cooperation.

R&D Cooperation: Each high-tech firm has its knowledge. At the R&D cooperation stage, high-tech firms establish a research joint venture, where they pool their knowledge and jointly hire researchers. In a "laboratory," a group of researchers combines the knowledge of different firms in order to produce better knowledge for a firm. There are as many laboratories (or different knowledge production processes) as there are high-tech firms. This research joint venture takes into account the effect of the accumulation of one type of knowledge on the accumulation of other types of knowledge.[36]

In such a case high-tech firms take (1.19) as given and jointly solve the following optimal problem.

$$\max_{NL_r} \int_{\bar{t}}^{+\infty} \left[\sum_{j=1}^{N(t)} \pi_j(t) \right] \exp\left[-\int_{\bar{t}}^{t} r(s)\, ds \right] dt$$

$$s.t.$$

$$\sum_{j=1}^{N} \pi_j = \sum_{j=1}^{N} \left(p_{x_j} \lambda_j - w \right) L_{x_j} - wNL_r, \tag{1.145}$$

$$x_j = \lambda_j L_{x_j}, \tag{1.146}$$

$$\dot{\lambda}_j = \xi \left(\sum_{i=1}^{N} \lambda_i^{\alpha} \right) \lambda_j^{1-\alpha} L_{r_j}. \tag{1.147}$$

The optimal rules for R&D that follow from this problem are

$$\left[L_{r_j} \right] : w = q_{\lambda_j} \frac{\dot{\lambda}_j}{L_{r_j}}, \tag{1.148}$$

[35] It might be argued that firms' cooperation in R&D increases the odds that they will collude in the product market. I rule this out in order to focus on the differences between knowledge exchange mechanisms.

[36] An alternative cooperation mode would be high-tech firms in the R&D stage jointly hiring researchers and producing the same knowledge for all. In such a case, the knowledge accumulation process is $\dot{\lambda} = \xi \lambda N L_r$. It can be easily shown that the decentralized equilibrium outcome of this cooperation mode is no different than the outcome of the cooperation mode offered in this section.

$$[\lambda_j]: \frac{\dot{q}_{\lambda_j}}{q_{\lambda_j}} = r - \left(\sum_{j=1}^{N} \frac{e_j^k - 1}{e_j^k} \frac{p_{x_j}}{q_{\lambda_j}} L_{x_j} + \frac{\partial \dot{\lambda}_j}{\partial \lambda_j} \right), \tag{1.149}$$

where

$$\frac{\partial \dot{\lambda}_j}{\partial \lambda_j} = \xi L_{r_j} \tag{1.150}$$
$$\times \left\{ 1 + (1-\alpha) \left(\sum_{i=1, i\neq j}^{N} \frac{\lambda_i}{\lambda_j} \right)^{\alpha} + \alpha \left[\sum_{i=1, i\neq j}^{N} \left(\frac{\lambda_i}{\lambda_j} \right)^{-(1-\alpha)} \frac{\partial \lambda_i}{\partial \lambda_j} \right] \right\},$$

and

$$\frac{\partial \lambda_i}{\partial \lambda_j} = \frac{\partial \lambda_i}{\partial t} \frac{\partial t}{\partial \lambda_j} = \left(\frac{\lambda_i}{\lambda_j} \right)^{1-\alpha} \frac{L_{r_i}}{L_{r_j}}. \tag{1.151}$$

The third term in the second line of (1.150) illustrates the effect of the accumulation of the jth type of knowledge (the knowledge of high-tech firm j) on the accumulation of the remaining types of knowledge.

In a symmetric equilibrium, according to (1.147), the growth rate of knowledge is

$$g_\lambda = \xi N L_r. \tag{1.152}$$

The rate of return on knowledge accumulation can be derived from (1.19), and (1.148)-(1.151). It is the same as (1.31), where $I^1_{S.2-3} = 0$.

The growth rates of quantities and prices that characterize the essential dynamics of this model, if there is R&D cooperation, are given by (1.104)-(1.108) and

$$g_w = g_{q_\lambda} + g_\lambda. \tag{1.153}$$

This equation is the counterpart of (1.109).

Combining (1.31) with (1.19), (1.32), (1.36), (1.37), (1.104)-(1.108), (1.148), (1.152), and (1.153) gives a differential equation in L_r,

$$\dot{L}_r = \frac{L - NL_r}{N\left[(1+\mu)(\theta-1)+1\right]} \tag{1.154}$$
$$\times \left\{ \left[(\theta-1)(\sigma+\mu) + D^k \right] \xi N L_r - \left(\xi D^k L - \rho \right) \right\},$$

which is the counterpart of (1.110).

Let $\theta \geq 1$ and (1.41) hold. Therefore, given that the first term of this differential equation is non-negative, there is unique L_r such that (1.154) is stable and

$NL_r, NL_x, L_Y \in (0, L)$,

$$L_r = \frac{1}{\xi N} \frac{\xi D^k L - \rho}{(\theta - 1)(\sigma + \mu) + D^k}.$$

Combining this expression with the relations between NL_x and L_Y, (1.32), and NL_x and NL_r, (1.37), and (1.152) gives the equilibrium allocations of labor force and growth rates of final output and knowledge

$$\begin{aligned}
NL_r^{NE} &= \frac{1}{\xi} \frac{\xi D^k L - \rho}{(\theta - 1)(\sigma + \mu) + D^k}, \\
NL_x^{NE} &= D^k \frac{(\theta - 1)(\sigma + \mu) L + \frac{1}{\xi}\rho}{(\theta - 1)(\sigma + \mu) + D^k}, \\
L_Y^{NE} &= \frac{1 - \sigma}{\sigma b^k} D^k \frac{[(\theta - 1)(\sigma + \mu)] L + \frac{1}{\xi}\rho}{(\theta - 1)(\sigma + \mu) + D^k}, \\
g_Y^{NE} &= (\sigma + \mu) g_\lambda^{NE}, \\
g_\lambda^{NE} &= \frac{\xi D^k L - \rho}{(\theta - 1)(\sigma + \mu) + D^k}.
\end{aligned}$$

Therefore, in a decentralized equilibrium with no entry and R&D collaboration, if (1.41) holds, the economy makes a discrete jump to a balanced growth path. Further, the growth rates and labor force allocations are the same when there is knowledge licensing (S.1) and R&D collaboration (CO). This means that if there is no (continuous) entry, knowledge licensing and R&D cooperation deliver equivalent equilibrium outcomes. Therefore, the policy (1.93)-(1.94) also leads to the first-best outcome in terms of allocations and growth rates in this case.

Further, in line with the results offered in the section where I discuss policies in order to have the socially optimal number of high-tech firms, there need to be lump-sum transfers to high-tech firms given by (1.95). These transfers make sure profits are greater than zero for any finite N and are zero for $N = +\infty$.

When there is continuous entry into the high-tech industry, equations (1.109) and (1.153) identify the difference between R&D cooperation (CO) and knowledge licensing (S.1). The rate of return on knowledge accumulation when there is knowledge licensing declines with continuous entry of firms ($\dot{N} > 0$). In contrast, when there is R&D cooperation, it does not do so because in R&D cooperation, firms choose R&D expenditures to maximize joint profits. Meanwhile, in case when there is knowledge licensing, entry erodes the profits of and returns on the knowledge accumulation of high-tech firms.

It can be easily shown that when there is continuous entry and R&D cooperation, the growth rate of knowledge/productivity is

$$g_{\lambda}^{CE} = \frac{\xi DL - \rho}{(\theta - 1)\frac{(\varepsilon-1)(\sigma+\mu)}{\varepsilon-1-(\sigma+\mu)} + D}. \tag{1.155}$$

This implies that the policy (1.93)-(1.94) leads to the first best outcome in terms of allocations and growth rates in this case.

Comparing (1.127) and (1.155), it is straightforward to notice that

$$g_{\lambda}^{CE} > g_{\lambda}^{CE,S.1-2},$$

because continuous entry ($\dot{N} > 0$) into high-tech industry decreases the returns on knowledge accumulation if high-tech firms engage in R&D disjointly.

Appendix E.2

In this section I show that adding knowledge depreciation and spillovers when there is knowledge licensing does not alter the main results. I consider exclusively S.1 and S.3 cases and the decentralized equilibrium of the model. I further assume that there are exogenous barriers to high-tech industry entry.

In order to support symmetric equilibrium, I assume that the rate of depreciation of knowledge is the same across high-tech firms, δ (> 0). This implies that the knowledge accumulation processes when there is no knowledge exchange among high-tech firms (S.3) can be written as

$$\dot{\lambda}_j = \xi \tilde{\lambda} \lambda_j^{1-\alpha} L_{r_j} - \delta \lambda_j. \tag{1.156}$$

Meanwhile, adding spillovers in the knowledge accumulation process in case there is knowledge licensing results in

$$\dot{\lambda}_j = \xi \left[\sum_{i=1}^{N} \hat{\lambda}_i \left(u_{i,j}\lambda_i\right)^{\alpha_1} \right] \lambda_j^{\alpha_2} L_{r_j} - \delta \lambda_j, \tag{1.157}$$

$$\alpha_1 + \alpha_2 > 1 - \alpha,$$

where I assume that in equilibrium

$$\hat{\lambda}_i \equiv \left(u_{i,j}\lambda_i\right)^{1-\alpha_1-\alpha_2}.$$

In this setup, $1-\alpha_1-\alpha_2$ can be thought to represent the bargaining power of licensees.

The optimal problem of high-tech firm j in such a case is given by (1.17), where (1.12) and (1.15) are replaced by (1.157) and (1.156), respectively.

From the optimal problem it can be shown that the demand functions for the labor force in production and R&D are then given by

$$\left[L_{x_j}\right] : w = \lambda_j p_{x_j} \left(1 - \frac{1}{e_j^k}\right), \tag{1.158}$$

$$\left[L_{r_j}\right] : w = q_{\lambda_j} \frac{\partial \dot{\lambda}_j}{\partial L_{r_j}}. \tag{1.159}$$

When there is knowledge licensing (and spillovers; S.1), the returns on knowledge accumulation are

$$[\lambda_j] : \frac{\dot{q}_{\lambda_j}}{q_{\lambda_j}} = r - \left(\frac{e_j^k - 1}{e_j^k} \frac{p_{x_j}}{q_{\lambda_j}} L_{x_j} + \frac{\partial \dot{\lambda}_j}{\partial \lambda_j} + \sum_{i=1, i\neq j}^{N} \frac{p_{u_{j,i}\lambda_j} u_{j,i}}{q_{\lambda_j}} \right),$$

where

$$\frac{\partial\dot{\lambda}_j}{\partial\lambda_j} = \xi\lambda_j^{\alpha_2-1}L_{r_j}\left[\alpha_2\sum_{i=1}^{N}\hat{\lambda}_i\left(u_{i,j}\lambda_i\right)^{\alpha_1} + \alpha_1\hat{\lambda}_j\lambda_j^{\alpha_1}\right] - \delta,$$

and the supply of and demand for knowledge are

$$[u_{j,i}] : u_{j,i} = 1,\ \forall i \neq j,$$
$$[u_{i,j}] : p_{u_{i,j}\lambda_i} = q_{\lambda_j}\xi\alpha_1\hat{\lambda}_i\left(u_{i,j}\lambda_i\right)^{\alpha_1-1}\lambda_j^{\alpha_2}L_{r_j},\ \forall i \neq j.$$

Meanwhile, when there is no exchange of knowledge among high-tech firms (S.3), the returns on knowledge accumulation are

$$[\lambda_j] : \frac{\dot{q}_{\lambda_j}}{q_{\lambda_j}} = r - \left[\frac{e_j^k - 1}{e_j^k}\frac{p_{x_j}}{q_{\lambda_j}}L_{x_j} + (1-\alpha)\,\xi\tilde{\lambda}\lambda_j^{-\alpha}L_{r_j} - \delta\right].$$

In a symmetric equilibrium, when there is knowledge licensing (S.1) and no exchange of knowledge among high-tech firms (S.3) returns on knowledge accumulation can be re-written as

$$g_{q_\lambda} = r + \delta - (g_\lambda + \delta)\left(\frac{L_x}{L_r} + 1 - I_{S.3}^{1-\alpha}\right), \tag{1.160}$$

where $I_{S.3}^{\alpha}$ measures the magnitude of not appropriated returns on R&D (i.e., in S.1 the bargaining power of licensees):

$$I_{S.3}^{\alpha} = \begin{cases} 1 - \alpha_1 - \alpha_2 \ for\ S.1, \\ \alpha\ for\ S.3. \end{cases}$$

Using (1.37), (1.104)-(1.109), (1.158) and (1.159), this expression can be re-written as a differential equation in L_r,

$$\dot{L}_r = \frac{L - NL_r}{N\left[(\theta-1)(1+\mu)+1\right]}\times$$
$$\left(\left[(\theta-1)(\sigma+\mu) + D^k + 1 - I_{S.3}^{1-\alpha}\right]\xi I_{S.1-2}^{N}L_r - \right.$$
$$\left.\left\{\xi D^k\frac{I_{S.1-2}^{N}}{N}L + \left[(\theta-1)(\sigma+\mu) + D^k\right]\delta - \rho\right\}\right).$$

Let

$$\xi D^k\frac{I_{S.1-2}^{N}}{N}L - I_{S.3}^{\alpha}\delta - \rho > 0.$$

This differential equation is stable if

$$L_r = \frac{1}{\xi I_{S.1-2}^{N}}\frac{\xi D^k\frac{I_{S.1-2}^{N}}{N}L + \left[(\theta-1)(\sigma+\mu) + D^k\right]\delta - \rho}{(\theta-1)(\sigma+\mu) + D^k + I_{S.3}^{\alpha}}.$$

This implies that the economy immediately jumps to a balanced growth path, where labor force allocations and growth rates of final output and knowledge are

$$
\begin{aligned}
NL_r &= \frac{N}{\xi I_{S.1-2}^N} \frac{\xi D^k \frac{I_{S.1-2}^N}{N} L + \left[(\theta - 1)(\sigma + \mu) + D^k \right] \delta - \rho}{(\theta - 1)(\sigma + \mu) + D^k + I_{S.3}^\alpha}, \\
NL_x &= D^k (L - NL_r), \\
L_Y &= \frac{1 - \sigma}{\sigma b^k} NL_x, \\
g_Y &= (\sigma + \mu) g_\lambda, \\
g_\lambda &= \frac{\xi D^k \frac{I_{S.1-2}^N}{N} L - I_{S.3}^\alpha \delta - \rho}{(\theta - 1)(\mu + \sigma) + D^k + I_{S.3}^\alpha}.
\end{aligned}
$$

Therefore,

$$
\frac{\partial g_\lambda}{\partial \delta} < 0, \frac{\partial NL_r}{\partial \delta} > 0, \frac{\partial NL_x}{\partial \delta} < 0, \frac{\partial L_Y}{\partial \delta} < 0,
$$

and

$$
\frac{\partial g_\lambda}{\partial I_{S.3}^{1-\alpha}} < 0, \frac{\partial NL_r}{\partial I_{S.3}^{1-\alpha}} < 0, \frac{\partial NL_x}{\partial I_{S.3}^{1-\alpha}} > 0, \frac{\partial L_Y}{\partial I_{S.3}^{1-\alpha}} > 0. \tag{1.161}
$$

Relationships (1.161) imply that the growth rate of productivity and labor force allocation to productivity/knowledge accumulation decrease with the degree of not appropriated returns on knowledge accumulation. Meanwhile, NL_x and L_Y increase with it. This is analogous to the results in section Entry Regime 1.

Appendix E.3

In this section, I relax the assumption that there are externalities within high-tech firms in two ways and present the main properties of the model. First, I assume that there are decreasing returns to knowledge accumulation at the firm-level unless there is an exchange of knowledge among high-tech firms. Next, I assume instead that there are no externalities within high-tech firms and, as in the main text, returns on knowledge accumulation are constant even if there is no exchange of knowledge.

I have assumed that N is a real number. If N also changes continuously, then in the sums in (1.12) and (1.13), each firm has zero size. Since λ of each firm is finite, dropping firm j or any finite number of firms from those sums makes no difference for the inference.

If N changes discretely (and each firm has unit size), I assume that $N-1>1$ so that the exchange of knowledge can only increase the productivity of researchers. In such a circumstance, I assume that if there is knowledge licensing, the knowledge accumulation process of high-tech firm j is given by

$$\dot{\lambda}_j = \xi \left[\sum_{i=1, i \neq j}^{N} (u_{i,j} \lambda_i)^{\alpha} \right] \lambda_j^{1-\alpha} L_{r_j}. \tag{1.162}$$

This is the counterpart of (1.12), where $u_{j,j} \equiv 0$. In turn, if there are knowledge spillovers, the knowledge accumulation process is given by (1.13), where

$$\tilde{\Lambda} \equiv \sum_{i=1, i \neq j}^{N} \lambda_i^{\alpha}. \tag{1.163}$$

If there is no knowledge exchange among high-tech firms, I assume that the knowledge accumulation process is given by (1.15), where

$$\tilde{\lambda} \equiv 1. \tag{1.164}$$

Therefore, the counterparts of (1.24), (1.28), and (1.29) are given by

$$\frac{\partial \dot{\lambda}_j}{\partial \lambda_j} = \xi (1-\alpha) \left[\sum_{i=1, i \neq j}^{N} \left(\frac{u_{i,j} \lambda_i}{\lambda_j} \right)^{\alpha} \right] L_{r_j}, \tag{1.165}$$

$$\frac{\partial \dot{\lambda}_j}{\partial \lambda_j} = \xi (1-\alpha) \left[\sum_{i=1, i \neq j}^{N} \left(\frac{\lambda_i}{\lambda_j} \right)^{\alpha} \right] L_{r_j}, \tag{1.166}$$

$$\frac{\partial \dot{\lambda}_j}{\partial \lambda_j} = \xi (1-\alpha) \lambda_j^{-\alpha} L_{r_j}. \tag{1.167}$$

I further consider a symmetric equilibrium in the high-tech industry. For the subsequent analysis, it is useful to define function $I_{S.1-2}^{N-1}$ as

$$I_{S.1-2}^{N-1}=\begin{cases}\lambda^{-\alpha}\ for\ S.3,\\ N-1\ otherwise.\end{cases}$$

Using this definition, the growth rate of knowledge in the high-tech industry in all setups (S.1-3) can be re-written as

$$g_{\lambda}=\xi I_{S.1-2}^{N-1}L_{r}. \tag{1.168}$$

The (internal) rate of return on knowledge accumulation can be obtained from the optimal rules of high-tech firm j: (1.19), (1.20), and (1.23), (1.27), and (1.165)-(1.167). It is given by (1.31),

$$g_{q_{\lambda}}=r-g_{\lambda}\left(\frac{L_{x}}{L_{r}}+1-\alpha I_{S.2-3}^{1}\right),$$

Combining (1.31) with (1.19), (1.20), (1.32), (1.36), (1.37), (1.40), (1.104)-(1.109), and (1.168) gives the counterpart of (1.110),

$$\begin{aligned}\dot{L}_{r}=&\frac{L-NL_{r}}{N\left[\left(1+\mu\right)\left(\theta-1\right)+1\right]}\\&\times\left\{\left[\left(\theta-1\right)\left(\sigma+\mu\right)+\alpha I_{S.2-3}^{1}+D^{k}\right]\xi\frac{I_{S.1-2}^{N-1}}{N}NL_{r}-\left(\xi D^{k}\frac{I_{S.1-2}^{N-1}}{N}L-\rho\right)\right\}.\end{aligned} \tag{1.169}$$

Assuming that

$$\xi D^{k}\frac{N-1}{N}L-\rho>0,$$

if there is an exchange of knowledge, the stable solution of this differential equation is

$$NL_{r}=\frac{1}{\xi}\frac{\xi D^{k}L-\frac{N}{N-1}\rho}{\left(\theta-1\right)\left(\sigma+\mu\right)+\alpha I_{S.2-3}^{1}+D^{k}}.$$

Therefore, g_{λ} is given by

$$g_{\lambda}=\frac{\xi D^{k}\frac{N-1}{N}L-\rho}{\left(\theta-1\right)\left(\sigma+\mu\right)+\alpha I_{S.2-3}^{1}+D^{k}}.$$

This implies that the comparative statics with respect to σ, μ, α, ε, and the type of competition presented in section Entry Regime 1 hold. Moreover, g_{λ} increases with N, and at least for a sufficiently high N ($N>2$), it is concave in N.

Meanwhile, when there is no exchange of knowledge, the expression (1.169) is a second-order differential equation in knowledge λ. It describes the path of λ. In the steady-state, the growth rate of knowledge and the labor force allocation to knowledge accumulation are zero. Therefore, labor force allocations to high-tech and final goods production are given by (1.48) and (1.49).

No Knowledge Externalities within High-tech Firms

In this sub-section, I assume that when there are knowledge spillovers among high-tech firms the knowledge accumulation process is given by

$$\dot{\lambda}_j = \xi \left[\lambda_j + \tilde{\Lambda} \lambda_j^{1-\alpha} \right] L_{r_j}, \tag{1.170}$$

where I assume that in equilibrium $\tilde{\Lambda}$ is given by (1.163). Meanwhile, when there is no exchange of knowledge among high-tech firms, I assume that the knowledge accumulation process is given by

$$\dot{\lambda}_j = \xi \lambda_j L_{r_j}. \tag{1.171}$$

From (1.170) it follows that (1.28) needs to be re-written as

$$\frac{\partial \dot{\lambda}_j}{\partial \lambda_j} = \xi \left[1 + (1-\alpha) \sum_{i=1, i \neq j}^{N} \left(\frac{\lambda_i}{\lambda_j} \right)^{\alpha} \right] L_{r_j}. \tag{1.172}$$

In turn, from (1.171), it follows that (1.29) needs to be re-written as

$$\frac{\partial \dot{\lambda}_j}{\partial \lambda_j} = \xi \left(1-\alpha\right) L_{r_j}. \tag{1.173}$$

The (internal) rate of return on knowledge accumulation can be derived from the optimal rules of high-tech firm j: (1.19), (1.20), (1.23), (1.27), (1.170), (1.171), (1.172), and (1.173). In a symmetric equilibrium, when there are knowledge spillovers, it is given by

$$g_{q_\lambda} = r - g_\lambda \left[\frac{L_x}{L_r} + \frac{1 + (1-\alpha)(N-1)}{N} \right], \tag{1.174}$$

and when there is no exchange of knowledge among high-tech firms, it is given by (1.31), where $I^1_{S.2-3} = 0$,

$$g_{q_\lambda} = r - g_\lambda \left(\frac{L_x}{L_r} + 1 \right). \tag{1.175}$$

From (1.175) it follows that if the knowledge accumulation process is given by (1.171), then the growth rate of knowledge and labor force allocations are given by (1.42)-(1.46), where $I^1_{S.2-3} = 0$ and $I^N_{S.1-2} = 1$. Therefore, the comparative statics with respect to σ, μ, ε, N and the type of competition presented in section Entry Regime 1 hold. Meanwhile, g_λ does not depend on α.

Further, combining (1.174) with (1.19), (1.20), (1.30), (1.32), (1.36), (1.37), (1.40), and (1.104)-(1.109) gives the counterpart of (1.110),

$$\dot{L}_r = \frac{L - NL_r}{N\left[(\theta-1)(1+\mu)+1\right]} \times \left\{ \left[(\theta-1)(\sigma+\mu) + D^k + \alpha \frac{N-1}{N} \right] \xi N L_r - \left(\xi D^k L - \rho \right) \right\}.$$

Therefore, the stable solution of this differential equation is

$$NL_r = \frac{1}{\xi} \frac{\xi D^k L - \rho}{(\theta-1)(\sigma+\mu) + D^k + \alpha \frac{N-1}{N}}.$$

This implies that the growth rate of knowledge is given by

$$g_\lambda^{S.2,NEx} = \frac{\xi D^k L - \rho}{(\theta-1)(\sigma+\mu) + D^k + \alpha \frac{N-1}{N}}.$$

Therefore, the comparative statics with respect to σ, μ, α, ε, and the type of competition presented in the section Entry Regime 1 hold.

If N changes continuously, then $\frac{N-1}{N}$ can be replaced by 1 and $g_\lambda^{S.2,NEx}$ increases and is concave in N. Meanwhile, when N changes discretely, $g_\lambda^{S.2,NEx}$ increases and is concave in N if parameters θ and ρ (and σ and μ) are sufficiently high and N is sufficiently small. However, if θ and ρ are low (e.g., $\theta = 1, \rho = 0$), or N is high, then $g_\lambda^{S.2,NEx}$ decreases and is convex in N. It can be further shown that

$$g_\lambda^{S.1} > g_\lambda^{S.2,NEx} > g_\lambda^{S.2},$$
$$\lim_{N\to+\infty} g_\lambda^{S.2,NEx} = \lim_{N\to+\infty} g_\lambda^{S.2}.$$

It is also worth noting that in these cases with cost-free entry, the allocations and growth rates depend on the toughness and intensity of competition. This is because in this case the size of the firm relative to the market $\frac{N-1}{N}$ matters for the amount of knowledge that it can receive and for spillovers.

Appendix E.4

In this section, I present the main properties of the model if high-tech firms take into account the effect of knowledge accumulation on the price of knowledge $p_{u_{j,i}\lambda_j}$. Further, I offer a policy that if implemented in a decentralized equilibrium will lead to socially optimal outcomes.[37]

The high-tech firms in this case internalize the demand (1.23). Therefore, the profit function of high-tech firm j "at the stage" where it designs its supply of knowledge and knowledge accumulation is

$$\begin{aligned}\pi_j &= p_{x_j}x_j - w\left(L_{x_j}+L_{r_j}\right)\\ &+\left[\alpha\xi\sum_{i=1,i\neq j}^{N} q_{\lambda_i}\left(u_{j,i}\lambda_j\right)^{\alpha}\lambda_i^{1-\alpha}L_{r_i}-\sum_{i=1,i\neq j}^{N} p_{u_{i,j}\lambda_i}\left(u_{i,j}\lambda_i\right)\right].\end{aligned}$$

This implies that everything else is the same and (1.25) needs to be re-written as

$$[\lambda_j]:\frac{\dot{q}_{\lambda_j}}{q_{\lambda_j}} = r-\left[\frac{e_j^k-1}{e_j^k}\frac{p_{x_j}}{q_{\lambda_j}}L_{x_j}+\frac{\partial\dot{\lambda}_j}{\partial\lambda_j}+\alpha^2\xi\sum_{i=1,i\neq j}^{N}\frac{q_{\lambda_i}\left(u_{j,i}\lambda_j\right)^{\alpha}\lambda_i^{1-\alpha}L_{r_i}}{q_{\lambda_j}\lambda_j}\right].$$

Therefore, in symmetric equilibrium the rate of return on knowledge accumulation is

$$g_{q_\lambda} = r-g_\lambda\left[\frac{L_x}{L_r}+1-\alpha\left(1-\alpha\right)\frac{N-1}{N}\right]. \tag{1.176}$$

In this expression, the third term in square brackets captures the adverse effect of higher knowledge accumulation on the price of knowledge.

Combining (1.104)-(1.109), (1.37), and (1.176) gives the counterpart of (1.110),

$$\begin{aligned}\dot{L}_r &= \frac{L-NL_r}{N\left[\left(1+\mu\right)\left(\theta-1\right)+1\right]}\\ &\times\left\{\left[\left(\theta-1\right)\left(\sigma+\mu\right)+D^k+\alpha\left(1-\alpha\right)\frac{N-1}{N}\right]\xi NL_r-\left(\xi D^kL-\rho\right)\right\}.\end{aligned}$$

Therefore, in equilibrium

$$\begin{aligned}NL_r^{NE,M} &= \frac{1}{\xi}\frac{\xi D^kL-\rho}{\left(\theta-1\right)\left(\sigma+\mu\right)+D^k+\alpha\left(1-\alpha\right)\frac{N-1}{N}},\\ NL_x^{NE,M} &= D^k\frac{\left[\left(\theta-1\right)\left(\sigma+\mu\right)+\alpha\left(1-\alpha\right)\frac{N-1}{N}\right]L+\frac{1}{\xi}\rho}{\left(\theta-1\right)\left(\sigma+\mu\right)+D^k+\alpha\left(1-\alpha\right)\frac{N-1}{N}},\end{aligned}$$

[37] I assume that price discrimination is not feasible. This is necessary in order to avoid the problem of determining the price of durable goods (Coase, 1972). In this framework it can be supported, for example, by assumption that the licensors have to license their entire knowledge (at a uniform price). Another assumption that could support this is licensors rent (but do not sell) their knowledge and cannot monitor its use.

$$
\begin{aligned}
L_Y^{NE,M} &= \frac{1-\sigma}{\sigma b^k} N L_x, \\
g_\lambda^{NE,M} &= \xi N L_r^{NE,M},
\end{aligned}
$$

where I use M in order to indicate that the firms are price setters in the market for knowledge in the sense that they internalize the effect of knowledge accumulation on the price of knowledge. If N changes continuously, then $\frac{N-1}{N}$ can be replaced by 1 in all of these expressions.

Comparing these results with (1.42)-(1.46) it is clear that for any given N

$$
\begin{aligned}
& NL_r^{NE,S.1} > NL_r^{NE,M} > NL_r^{NE,S.2}, \\
& NL_x^{NE,S.1} < NL_x^{NE,M} < NL_x^{NE,S.2}, \\
& L_Y^{NE,S.1} < L_Y^{NE,M} < L_Y^{NE,S.2}, \\
& g_\lambda^{NE,S.1} > g_\lambda^{NE,M} > g_\lambda^{NE,S.2}.
\end{aligned}
$$

Therefore, under the cost-free entry assumption

$$
g_\lambda^{CFE,S.1} > g_\lambda^{CFE,M} > g_\lambda^{CFE,S.2},
$$

and

$$
N^{CFE,S.1} < N^{CFE,M} < N^{CFE,S.2}.
$$

This is because ZP is a monotonically decreasing function of N.

If N changes continuously, then $g_\lambda^{NE,M}$ increases and is concave in N. It is increases and is concave in N also when N changes discretely if parameters θ and ρ (and σ and μ) are sufficiently high and N is sufficiently small. However, if θ and ρ are low (e.g., $\theta = 1, \rho = 0$), or N is high, then $g_\lambda^{NE,M}$ can decrease and be convex in N.

These results imply that if high-tech firms take into account the effect of knowledge accumulation on the price of knowledge they innovate less. Therefore, the economy would grow at a lower rate than an economy where high-tech firms do not take into account this effect. Moreover, since

$$
g_\lambda^{SP} > g_\lambda^{S.1},
$$

the economy (again) fails to grow at the socially optimal rate and fails to have socially optimal labor allocations.

A policy that can equate decentralized equilibrium allocations and growth rates to their socially optimal counterparts subsidizes the demand for high-tech goods and high-tech firms' demand for knowledge. It can be shown that this policy is

$$\tau_x = \frac{e^k \mu + \sigma}{e^k (\sigma + \mu)},$$
$$\tau_\lambda = 1 - \alpha.$$

Further, in line with the results offered in the section where I discuss policies in order to have the socially optimal number of high-tech firms, there need to be lump-sum transfers to high-tech firms given by (1.95). These transfers make sure profits are greater than zero for any finite N and are zero for $N = +\infty$.

The profit function of high-tech firms can be re-written as

$$\pi = wL_x \left[\frac{1}{e^k - 1} - \left(1 - \alpha \frac{N-1}{N} \frac{\tau_\lambda}{1 - \tau_\lambda}\right) \frac{L_r}{L_x} + \tau_\pi^M \right], \tag{1.177}$$

where

$$\frac{L_r}{L_x} = \frac{L_r^{SP}}{L_x^{SP}} = \frac{\xi D^{SP} L - \rho}{(\theta - 1)(\sigma + \mu)\xi D^{SP} L + D^{SP} \rho}.$$

Therefore,

$$\tau_\pi^M = \alpha \frac{L_r}{L_x} - \frac{1}{\varepsilon - 1}.$$

This implies that unlike τ_π from (1.96), the rate τ_π^M can be negative, for example, if $\alpha \approx 0$.[38]

[38] In order to have a meaningful policy, a parameter restriction is required so that τ_π^M, which solves zero profit condition for (1.177), increases in N.

Appendix E.5

In this section, I present the main properties of the model when final goods producers do not hire labor ($\sigma = 1$), or L_Y is fixed.

If $\sigma = 1$, then (3.1) is given by

$$Y = \tilde{X}X, \tag{1.178}$$

and final goods producers' demand for a high-tech goods bundle is given by

$$P_X = \tilde{X}. \tag{1.179}$$

Assuming a symmetric equilibrium, this implies that (1.105) needs to be re-written as

$$g_Y = (1+\mu)\, g_X, \tag{1.180}$$

and (1.107) needs to be replaced by

$$g_{q_\lambda} = \mu\left(g_\lambda + g_{L_x}\right), \tag{1.181}$$

which follows from (1.5), (1.8), (1.11), (1.19), (1.20), and (1.179).

Since $L_Y = 0$, the labor market clearing condition is

$$L = NL_x + NL_r. \tag{1.182}$$

Combining (1.31) with (1.30), (1.40), (1.104), (1.106), (1.108), and (1.180)-(1.182) gives a differential equation in L_r,

$$\begin{aligned}\dot{L}_r = &\frac{L - NL_r}{N\left[(\theta-1)(1+\mu)+1\right]}\\ &\times\left\{\left[(\theta-1)(1+\mu)+\alpha I^1_{S.2-3}+1\right]\xi I^N_{S.1-2}L_r - \left(\xi\frac{I^N_{S.1-2}}{N}L-\rho\right)\right\}.\end{aligned}$$

Therefore, labor force allocations and growth rates of final output and knowledge/productivity are given by

$$\begin{aligned}NL_r &= \frac{N}{\xi I^N_{S.1-2}}\frac{\xi\frac{I^N_{S.1-2}}{N}L-\rho}{(\theta-1)(1+\mu)+\alpha I^1_{S.2-3}+1},\\ NL_x &= \frac{\left[(\theta-1)(1+\mu)+\alpha I^1_{S.2-3}\right]L+\frac{N}{\xi I^N_{S.1-2}}\rho}{(\theta-1)(1+\mu)+\alpha I^1_{S.2-3}+1},\\ g_Y &= (1+\mu)\,g_\lambda,\end{aligned}$$

$$g_\lambda = \frac{\xi \frac{I^N_{S.1-2}}{N} L - \rho}{(\theta - 1)(1 + \mu) + \alpha I^1_{S.2-3} + 1}.$$

Given that in this case $L_Y = 0$, these expressions coincide with (1.42)-(1.46), in the limit where $\sigma = 1$. They suggest that if $\sigma = 1$, labor force allocations and, therefore, growth rates do not depend on competitive pressure in the high-tech industry. This is because, in this case, there are no relative price distortions in the sense that all prices are affected in the same way.

In case, however, $L_Y \equiv \zeta_1 > 0$, then from (1.32) and (1.36) it follows that

$$NL_x = \frac{\sigma}{1 - \sigma} \frac{e^k - 1}{e^k} \zeta_1,$$

$$NL_r = L - \frac{e^k - \sigma}{(1 - \sigma) e^k} \zeta_1.$$

Increasing competitive pressure in the industry increases e in these expressions. Therefore, NL_x increases with e, whereas NL_r declines with it, which means that increasing the competitive pressure in this case increases the output of the industry but reduces the amount of resources devoted to innovation. This occurs because increasing the competitive pressure increases NL_x, and since L_Y is fixed, that reduces NL_r.

When the wage of researchers L_r is given $w_{L_r} \equiv \zeta_2 Z$, the demand for R&D labor in high-tech firm j is given by

$$w_{L_r} = q_{\lambda_j} \frac{\dot{\lambda}_j}{L_{r_j}}.$$

Combining this expression with (1.19) gives the relative demand for production labor. In symmetric equilibrium, the relative demand is

$$\xi I^N_{S.1-2} \frac{w}{w_{L_r}} = \frac{e - 1}{e} \frac{p_x}{q_\lambda}.$$

Combining these expressions with the returns on knowledge accumulation (1.23), and (1.24)-(1.29), gives

$$g_{w_{L_r}} = r - g_\lambda \left(\frac{w}{w_{L_r}} \frac{NL_x}{NL_r} - \alpha I^1_{S.2-3} \right).$$

Assuming that $g_{w_{L_r}} = g_w$ from this expression, (1.40) and (1.104)-(1.108), it follows then

$$-g_{L_x} = \frac{1}{(\theta - 1)(1 + \mu) + 1} \times \left\{ \left[(\theta - 1)(\sigma + \mu) + \alpha I^1_{S.2-3} \right] g_\lambda + \rho - g_\lambda \frac{w}{w_{L_r}} \frac{NL_x}{NL_r} \right\}.$$

In turn, from (1.37), it follows that

$$
\begin{aligned}
\dot{L}_r = & \frac{L - NL_r}{N\left[(1+\mu)(\theta-1)+1\right]} \\
& \times \left\{ \left[(\theta-1)(\sigma+\mu) + \alpha I^1_{S.2-3} + \frac{w}{w_{L_r}} D^k \right] \xi I^N_{S.1-2} L_r \right. \\
& \left. - \left(\xi \frac{I^N_{S.1-2}}{N} \frac{w}{w_{L_r}} D^k L - \rho \right) \right\}.
\end{aligned}
$$

Therefore, labor force allocation to R&D in the high-tech industry and the growth rate of knowledge are given by

$$
\begin{aligned}
NL_r &= \frac{N}{\xi I^N_{S.1-2}} \frac{\xi \frac{I^N_{S.1-2}}{N} \frac{w}{w_{L_r}} D^k L - \rho}{(\theta-1)(\sigma+\mu) + \alpha I^1_{S.2-3} + \frac{w}{w_{L_r}} D^k}, \\
g_\lambda &= \frac{\xi \frac{I^N_{S.1-2}}{N} \frac{w}{w_{L_r}} D^k L - \rho}{(\theta-1)(\sigma+\mu) + \alpha I^1_{S.2-3} + \frac{w}{w_{L_r}} D^k}.
\end{aligned}
$$

This implies that reducing the relative wage $\frac{w}{w_{L_r}}$ reduces innovation.

Appendix E.6

In this section, I use more general knowledge accumulation processes and present the main properties of the model for cases where there is an exchange of knowledge among high-tech firms (S.1-2), and the number of high-tech firms is fixed.

Let the knowledge accumulation have a CES form of

$$\dot{\lambda}_j = \xi \left[\sum_{i=1}^{N} (u_{i,j}\lambda_i)^{\alpha\frac{\varepsilon_1 - 1}{\varepsilon_1}} \right]^{\frac{\varepsilon_1}{\varepsilon_1 - 1}} \lambda_j^{1-\alpha} L_{r_j}, \tag{1.183}$$

or

$$\dot{\lambda}_j = \xi \left[\sum_{i=1}^{N} (u_{i,j}\lambda_i)^{\frac{\varepsilon_1 - 1}{\varepsilon_1}} \right]^{\alpha\frac{\varepsilon_1}{\varepsilon_1 - 1}} \lambda_j^{1-\alpha} L_{r_j}, \tag{1.184}$$

where $\varepsilon_1 > 0$. I call these cases G.1 and G.2– generalization 1 and generalization 2 –correspondingly.

Re-writing (1.23), (1.25), and (1.28) and using (1.23), it is straightforward to show that when there is an exchange of knowledge among high-tech firms (S.1-2) in a symmetric equilibrium, the returns on knowledge accumulation are given by (1.31). Meanwhile, the growth rate of λ in (1.183) is

$$g_\lambda = \xi N^{\frac{1}{\varepsilon_1 - 1}} N L_r. \tag{1.185}$$

and in (1.184), it is

$$g_\lambda = \xi N^{\frac{1-\varepsilon_1(1-\alpha)}{\varepsilon_1 - 1}} N L_r. \tag{1.186}$$

Defining

$$I_{G.1-2} = \begin{cases} N^{\frac{1}{\varepsilon_1 - 1}} \; for\ G.1, \\ N^{\frac{1-\varepsilon_1(1-\alpha)}{\varepsilon_1 - 1}} \; otherwise \end{cases}$$

and re-writing the growth rates gives

$$g_\lambda^{G.1-2} = \xi I_{G.1-2} N L_r. \tag{1.187}$$

Combining (1.187) with (1.31), (1.32), (1.37), (1.40), and (1.104)-(1.109) gives the analogue of the differential equation in L_r (1.110),

$$\dot{L}_r = \frac{L - NL_r}{N\left[(1+\mu)(\theta - 1) + 1\right]} \times \left\{ \left[(\theta - 1)(\sigma + \mu) + \alpha I^1_{S.2-3} + D^k\right] g_\lambda^{G.1-2} - \left(g_\lambda^{G.1-2} \frac{D^k L}{N L_r} - \rho \right) \right\}. \tag{1.188}$$

Assuming that

$$\xi I_{G.1-2} D^k L - \rho > 0,$$

the implication is that there is a unique L_r such that (1.188) is stable, and $NL_r, NL_x, L_Y \in (0, L)$. The level of L_r can be derived from the growth rate of λ that satisfies $\dot{L}_r = 0$ in (1.188),

$$g_{\lambda}^{G.1-2} = \frac{\xi I_{G.1-2} D^k L - \rho}{(\theta - 1)(\sigma + \mu) + \alpha I_{S.2-3}^1 + D^k}. \tag{1.189}$$

A sufficient condition to have the growth rate of λ as non-decreasing in N for any N is then

$$\frac{\partial I_{G.1-2}}{\partial N} \geq 0. \tag{1.190}$$

This condition is sufficient since $\frac{\partial D^k}{\partial N} > 0$, and $\lim_{N \to +\infty} D^k = const > 0$. It holds, for example, when $\varepsilon_1 > 1$ in case of G.1 and when $\varepsilon_1 > 1$, and α is close to 1 in the case of G.2.

Replacing $I_{G.1-2}$ with the arbitrary monotonic (and differentiable) function $\digamma(N)$ in (1.189) gives

$$g_{\lambda}^{G.3} = \frac{\xi \digamma(N) D^k L - \rho}{(\theta - 1)(\sigma + \mu) + \alpha I_{S.2-3}^1 + D^k}.$$

Such a growth rate of λ holds if, for example, (1.12) is multiplied by $\digamma(N)$:

$$\dot{\lambda}_j = \xi \digamma(N) \left[\sum_{i=1}^{N} (u_{i,j} \lambda_i)^{\alpha} \right] \lambda_j^{1-\alpha} L_{r_j}.$$

In this more general case, the sufficient conditions of having the growth rate of λ as non-decreasing in N for any N are

1. $$\frac{\partial \digamma(N)}{\partial N} \geq 0,$$

2. $$\begin{aligned} &\frac{\rho}{\xi \digamma(N) D^k L} \digamma(N) \frac{\partial D^k}{\partial N} + D^k \frac{\partial \digamma(N)}{\partial N} \geq 0, \\ &\lim_{N \to +\infty} \frac{\partial \digamma(N)}{\partial N} = 0, \\ &\lim_{N \to +\infty} \digamma(N) > 0. \end{aligned}$$

The first line of the second condition is weaker than (1.190) and holds as long as $\digamma(N) D^k$ grows with N at a sufficiently high rate.

An interesting case for when these conditions do not hold is

$$\digamma(N) = \frac{1}{N}.$$

In such a circumstance, the results for when there is an exchange of knowledge among high-tech firms (S.1-2) are similar to when there is no exchange of knowledge (S.3). In particular, the results for S.2 coincide with the results for S.3.

Furthermore, when there is cost-free entry, it can be shown that the analogues of (1.71)-(1.75) are

$$\begin{aligned}
e^k &= \frac{\xi\sigma F(N) L [1+\alpha+(\theta-1)(\sigma+\mu)]}{\xi\sigma F(N) L-\rho}, \\
g_\lambda &= \frac{\xi\sigma F(N) L-\rho}{(\theta-1)(\sigma+\mu)+\alpha I^1_{S.2-3}+1}, \\
NL_r &= \frac{1}{\xi F(N)} \frac{\xi\sigma F(N) L-\rho}{(\theta-1)(\sigma+\mu)+\alpha I^1_{S.2-3}+1}, \\
NL_x &= \frac{1}{\xi F(N)} \frac{\xi\sigma F(N) L\left[(\theta-1)(\sigma+\mu)+\alpha I^1_{S.2-3}\right]+\rho}{(\theta-1)(\sigma+\mu)+\alpha I^1_{S.2-3}+1}, \\
L_Y &= (1-\sigma) L.
\end{aligned}$$

Therefore, with this more general formulation of the R&D process, when there is cost-free entry and exchange of knowledge, labor force allocations depend on the toughness and intensity of competition in the high-tech industry.

Appendix E.7

In this section, I show that subsidies for the production of high-tech goods (τ_{L_x}) and R&D expenditures (τ_{L_r}) can also lead to first-best labor force allocations and growth rates. Under such a policy the profit function of high-tech firm j is

$$\begin{aligned}\pi_j = & \ p_{x_j}x_j - (1-\tau_{L_x})\, wL_{x_j} - (1-\tau_{L_r})\, wL_{r_j} \\ & + \left[\sum_{i=1,i\neq j}^{N} p_{u_{j,i}\lambda_j}\left(u_{j,i}\lambda_j\right) - \sum_{i=1,i\neq j}^{N} p_{u_{i,j}\lambda_i}\left(u_{i,j}\lambda_i\right)\right] + T_\pi .\end{aligned}$$

In turn, its demand for labor for the production of its high-tech good (1.19) and demand for R&D labor (1.20) are given by

$$\begin{aligned}\left[L_{x_j}\right] &: (1-\tau_{L_x})\, w = \lambda_j p_{x_j}\left(1-\frac{1}{e_j}\right), \\ \left[L_{r_j}\right] &: (1-\tau_{L_r})\, w = q_{\lambda_j}\frac{\dot{\lambda}_j}{L_{r_j}}.\end{aligned}$$

Assuming a symmetric equilibrium and combining these optimal rules with (1.6), (1.9), (1.24) and labor market clearing condition (1.36) gives the counterparts of the relation between NL_x and L_Y (1.32), returns on knowledge accumulation (1.31), and the relation between NL_x and NL_r.

$$\begin{aligned}NL_x &= \frac{1}{1-\tau_{L_x}}\frac{\sigma}{1-\sigma}b^k L_Y, \\ g_{q_\lambda} &= r - g_\lambda\left(\frac{1-\tau_{L_x}}{1-\tau_{L_r}}\frac{L_x}{L_r}+1\right), \\ NL_x &= D^{GO}\left(L - NL_r\right),\end{aligned}$$

where

$$D^{GO} = \left[(1-\tau_{L_x})\,\frac{1-\sigma}{\sigma}\frac{1}{b^k}+1\right]^{-1}.$$

Assuming that subsidy rates are constant and combining these conditions with (1.104)-(1.109) gives the counterpart of (1.110),

$$\begin{aligned}\dot{L}_r = & \ \frac{L-NL_r}{N\left[(1+\mu)(\theta-1)+1\right]} \\ & \times\left\{\left[(\theta-1)(\sigma+\mu)+D^{GO}\frac{1-\tau_{L_x}}{1-\tau_{L_r}}\right]\xi NL_r \right. \\ & \left. - \left(\xi D^{GO}\frac{1-\tau_{L_x}}{1-\tau_{L_r}}L-\rho\right)\right\}.\end{aligned}$$

Labor force allocations and the growth rate of knowledge g_λ then are

$$
\begin{aligned}
NL_r &= \frac{1}{\xi}\frac{\xi D^{GO}\frac{1-\tau_{L_x}}{1-\tau_{L_r}}L-\rho}{(\theta-1)(\mu+\sigma)+D^{GO}\frac{1-\tau_{L_x}}{1-\tau_{L_r}}},\\
NL_x &= D^{GO}\frac{(\theta-1)(\mu+\sigma)L+\frac{1}{\xi}\rho}{(\theta-1)(\mu+\sigma)+D^{GO}\frac{1-\tau_{L_x}}{1-\tau_{L_r}}},\\
L_Y &= (1-\tau_x)\left(1-\tau_{L_x}\right)\frac{1-\sigma}{\sigma b^k}NL_x,\\
g_\lambda &= \xi NL_r.
\end{aligned}
$$

Therefore, in order to have a socially optimal growth rate and labor allocations, it is sufficient to have

$$NL_r = NL_r^{SP}, NL_x = NL_x^{SP}.$$

In order to achieve such outcomes, it is sufficient to subsidize the expenditures of high-tech firms

$$\tau_{L_x} = \tau_{L_r} = \frac{e^k\mu+\sigma}{e^k(\sigma+\mu)},$$

In this case, τ_{L_x} and τ_{L_r} are equal because in the decentralized equilibrium, the relative price distortions affect the wages of L_x and L_r in the same way.

Appendix E.8

In this section, I offer comparative statics for the consumer and total welfare with respect to parameters α, ε, and N (when N is exogenous). The comparative statics are exclusively for the cases where there is an exchange of knowledge among high-tech firms (S.1-2) and Entry Regime 1 and 2: no entry and cost-free entry.

Using (3.11), (1.3), (3.1), (1.5), (1.11), (1.39), and that the economy is always on a balanced growth path, consumer welfare can be written as

$$U = -\frac{1}{\theta-1}\left\{N^{\frac{\sigma+\mu}{\varepsilon-1}}\left[\lambda(0)\,NL_x\right]^{\sigma+\mu}L_Y^{1-\sigma}\right\}^{1-\theta}\frac{1}{(\theta-1)(\sigma+\mu)g_\lambda+\rho} + \frac{1}{\rho}\frac{1}{\theta-1}. \tag{1.191}$$

Clearly, for the current analysis of consumer welfare it is enough to focus on a monotonic transformation of U:

$$\tilde{U} = -\left\{N^{\frac{\sigma+\mu}{\varepsilon-1}}\left[NL_x\right]^{\sigma+\mu}L_Y^{1-\sigma}\right\}^{1-\theta}\frac{1}{(\theta-1)(\sigma+\mu)g_\lambda+\rho}. \tag{1.192}$$

When there is no entry (Entry Regime 1), in these expressions g_λ is given by (1.46) and labor force allocations are $NL_r = \frac{1}{\xi}g_\lambda$, $NL_x = D^k(L-NL_r)$, and $L_Y = L - NL_x - NL_r$.

Meanwhile, as shown in the proof of Proposition 2, when there is no entry the producers' surplus is

$$NV = \frac{1}{(\theta-1)(\sigma+\mu)g_\lambda+\rho}\sigma\left\{N^{\frac{\sigma+\mu}{\varepsilon-1}}\left[\lambda(0)\,NL_x\right]^{\sigma+\mu}L_Y^{1-\sigma}\right\}\frac{1}{e^k} \times\left[1-\left(e^k-1\right)\frac{NL_r^{NE}}{NL_x^{NE}}\right]. \tag{1.193}$$

Therefore, when there is no entry, the total welfare is

$$W = U + NV = \frac{\left\{N^{\frac{\sigma+\mu}{\varepsilon-1}}\left[\lambda(0)\,NL_x\right]^{\sigma+\mu}L_Y^{1-\sigma}\right\}}{(\theta-1)(\sigma+\mu)g_\lambda+\rho} \times\left(-\frac{\left\{N^{\frac{\sigma+\mu}{\varepsilon-1}}\left[\lambda(0)\,NL_x\right]^{\sigma+\mu}L_Y^{1-\sigma}\right\}^{-\theta}}{\theta-1}+\sigma\frac{1}{e^k}\left[1-\left(e^k-1\right)\frac{NL_r^{NE}}{NL_x^{NE}}\right]\right) \tag{1.194}$$

When there is cost-free entry (Entry Regime 2), producers' surplus is zero, $NV = 0$, and the perceived elasticity of substitution e^k is given by (1.71).

Combining (1.71) with (1.21) and (1.22) gives the endogenous number of firms under Cournot and Bertrand types of competition

$$N^{CR} = \frac{(\varepsilon - 1)\,\xi\sigma L\left[1 + \alpha I^1_{S.2-3} + (\theta - 1)(\sigma + \mu)\right]}{\varepsilon(\xi\sigma L - \rho) - \xi\sigma L\left[1 + \alpha I^1_{S.2-3} + (\theta - 1)(\sigma + \mu)\right]}, \tag{1.195}$$

$$N^{BR} = \frac{(\varepsilon - 1)(\xi\sigma L - \rho)}{\varepsilon(\xi\sigma L - \rho) - \xi\sigma L\left[1 + \alpha I^1_{S.2-3} + (\theta - 1)(\sigma + \mu)\right]}, \tag{1.196}$$

where $N^{CR} > N^{BR}$. Clearly, in this case total welfare can be written as $W = \tilde{U}$.

Setting $I^1_{S.2-3} \equiv 1$, it is straightforward to notice that the inference from S.1 is a special case of the inference from S.2 when $\alpha \to 0$, i.e.,

$$\lim_{\alpha\to 0} g_\lambda^{S.2} = g_\lambda^{S.1}, \lim_{\alpha\to 0} e^{k,S.2} = e^{k,S.1}, \lim_{\alpha\to 0} N^{k,S.2} = N^{k,S.1}.$$

Therefore, the comparative statics can be performed for the more general S.2 case.

Because of high non-linearity of welfare functions analytical derivations of comparative statics are not trivial. I perform the comparative statics using numerical simulations, where L is normalized to 1 and the remaining parameters are from the following intervals:

$$\begin{aligned} &\theta \in [1, 10], \rho \in [0.01, 0.1], \sigma \in [0.01, 0.99], \mu \in [0.01, 0.99], \xi \in [0.1, 10], \\ &\alpha \in [0.01, 0.99], \varepsilon \in [1.1, 10], N \in [1.1, 20], \text{ and } \lambda(0) \in [1, 10] \end{aligned} \tag{1.197}$$

and satisfy parameter restrictions $\sigma + \mu < 1$, $\xi D^k L - \rho > 0$, $\varepsilon - 1 - \alpha - (\theta - 1)(\sigma + \mu) > 0$, $N^{BR} > 1$. I use the interval for N when there is no entry into the high-tech industry.

In order to distinguish no entry and cost-free entry, I again use superscripts NE and CFE and summarize the results in the following table.

Table 1.1: *Numerical Comparative Statics for S.1-2 Cases*

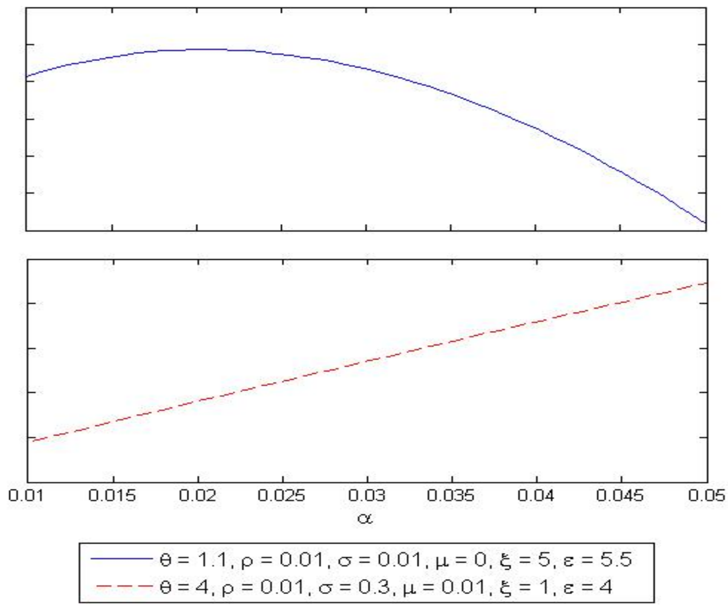
	W^{NE}	$\tilde{U}^{NE}$	W^{CFE}
α	$\pm$	$-$	$\pm$
ε	$\pm$	$\pm$	$-$
N	$\pm$	$+$	

Note: This table offers numerical comparative statics for cases when there is an exchange of knowledge among high-tech firms (S.1-2). The sign $+$ means a positive relationship, $-$ negative, and $\pm$ that the relationship depends on model parameters. When there is cost-free entry, N is not a parameter. Therefore, in the table there is no value in front of N for W^{CFE}. The values of parameters are from intervals (1.197) and satisfy parameter restrictions. Grids are equally spaced and each has 5 points.

Focusing on comparative statics with respect to α, the results indicate that when there is no entry, consumer welfare declines with α. This means that consumer welfare is higher when there is knowledge licensing (S.1) compared to when there are knowledge spillovers (S.2) if there is no entry. However, the sign of the derivative of total welfare with respect to α depends on model parameters. It also depends on model parameters when there is cost-free entry and coincides with the sign of the derivative for consumer welfare with respect to α.

Further, the results indicate that when there is cost-free entry, the sign of the derivative of total welfare with respect to α is positive when α is very close to zero. This means that, if there is cost-free entry and α is relatively small, total welfare is higher when there are knowledge spillovers (S.2) compared to when there is knowledge licensing (S.1). Figure 3.2 plots W^{CFE} as a function of α for Cournot-type competition.

Figure 1.2: *Total Welfare as a Function of α When There is Cost-free Entry*



In turn, the negative relation between W^{CFE} and ε follows from Proposition 13 and Corollary 8. Proposition 13 shows that when there is cost-free entry, the number of firms declines with ε. Meanwhile, Corollary 8 shows that allocations and growth rates do not depend on ε in such a case.

Appendix T.1

The elasticities of substitution between the knowledge that high-tech firm j licenses from other firms and between its knowledge and the knowledge of other firms can be derived from (1.12).

The elasticity of substitution between the knowledge licensed from firm m and firm k ($m \neq k$) is given by

$$\varepsilon^{\lambda}_{m,k} = \frac{1}{1-\alpha}.$$

In turn, the elasticity of substitution between the knowledge bought from firm k and firm j's own knowledge can be derived in the following way.

$$\varepsilon^{\lambda}_{j,k} = \frac{d\ln\left(\frac{u_{k,j}\lambda_k}{\lambda_j}\right)}{(1-\alpha)\, d\ln\left(\frac{u_{k,j}\lambda_k}{\lambda_j}\right) + d\ln\left[(1-\alpha)\sum\limits_{i=1, i\neq j}^{N}\left(\frac{u_{i,j}\lambda_i}{\lambda_j}\right)^{\alpha} + 1\right]}.$$

Denote

$$\frac{u_{k,j}\lambda_k}{\lambda_j} = z,$$

and re-write $\varepsilon^{\lambda}_{j,k}$ as

$$\varepsilon^{\lambda}_{j,k} = \frac{1}{1-\alpha+\alpha\frac{(1-\alpha)z^{\alpha}}{(1-\alpha)z^{\alpha}+(1-\alpha)\sum\limits_{i=1, i\neq j,k}^{N}\left(\frac{u_{i,j}\lambda_i}{\lambda_j}\right)^{\alpha}+1}}.$$

Since the third term in the denominator of $\varepsilon^{\lambda}_{j,k}$ is positive,

$$\varepsilon^{\lambda}_{j,k} < \varepsilon^{\lambda}_{m,k}.$$

This means that the elasticity of substitution between the firm's knowledge with the knowledge that it licenses from other firms is lower than the elasticity of substitution between the different types of knowledge that it licenses from other firms.

Chapter 2

The Impact of Telecommunication Technologies on Competition in Services and Goods Markets: Empirical Evidence

(Joint work with Anna Kochanova)

Abstract

In this paper we empirically show that a more intensive use and wider adoption of telecommunication technologies significantly increases the level of product market competition in services and goods markets. Our result is consistent with the view that the use of telecommunication technologies can lower the costs of entry. This finding is robust to various measures of competition and a range of specification checks.

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2.1 Introduction

"...[I]n most of the economy IT will help to increase competition.

Broadly speaking, the Internet reduces barriers to entry, because it is cheaper to set up a business online than to open a traditional shop or office. The Internet also makes it easier for consumers to compare prices. Both these factors increase competition."

The Economist, September 21, 2000

The internet is a type of telecommunication technology. Conjectures like this in *The Economist* indicate that there can be a positive relationship between the more intensive use and the wider adoption (hereafter, diffusion) of telecommunication technologies and competition in services and goods markets (for similar arguments see also Leff, 1984; McFarlan, 1984; Freund and Weinhold, 2004; Czernich, Falck, Kretschmer, and Woessmann, 2011). Another mechanism behind such a positive relation is that telecommunication technologies can lower information acquisition costs, which are argued to be significant for the decision on entry into a market (e.g., see Geroski, 1995b).

These arguments are certainly not conclusive, however. It may be argued as well that the diffusion of telecommunication technologies can help firms loosen competition. For example, firms can use the internet and other types of telecommunication networks for (extensive) advertisement of their products, which can help to increase product differentiation. In turn, lower information acquisition costs can help firms to learn about the demand and the general market environment. This can allow them to better target their marketing appeals and can increase price discrimination and product differentiation (for well-known examples see Taylor, 2004; Mikians, Gyarmati, Erramilli, and Laoutaris, 2012).

In this study, we empirically investigate the effect of the country-wide diffusion of telecommunication technologies on the competition in services and goods markets. In order to alleviate endogeneity concerns, we use a difference-in-differences framework in the spirit of Rajan and Zingales (1998). More specifically, we ask whether in countries where, *a priori*, the diffusion of telecommunication technologies is higher, the intensity of product market competition is disproportionately different in the industries that depend more on these technologies compared to the industries that depend less. We use evidence from 21 EU countries in order to establish our results.

Our results suggest that the diffusion of telecommunication technologies has a strong positive effect on the intensity of competition in services and goods markets. This supports conjectures such as in the quote above from *The Economist.*

According to the standard theoretical inference, our results imply that the diffusion of telecommunication technologies increases allocative efficiency in the economy.

Moreover, in line with many empirical studies (e.g., Nickell, Wadhwani, and Wall, 1992; Nickell, 1996; Disney, Haskel, and Heden, 2003), our findings imply significant productivity gains due to the diffusion of telecommunication technologies. According to, for example, Aghion et al. (2005), the diffusion may also imply higher innovative activity (see also Geroski, 1995a; Blundell et al., 1999).[2]

Our study also contributes to the ongoing debate about the impact of telecommunication technologies, as well as of information and communication technologies (ICT), on economic performance. Macro-level empirical studies suggest that the diffusion of these technologies has a positive impact on the development level and growth (e.g., Röller and Waverman, 2001; Czernich et al., 2011). Micro-level empirical studies, in turn, suggest that the use of telecommunication technologies and ICT can reduce price dispersion and average prices in online markets (e.g., Jensen, 2007; Lee, 1998; Strader and Shaw, 1999; Brynjolfsson and Smith, 2000). There can be various drivers behind these results. For instance, the literature on the economics of ICT (e.g., Jorgenson et al., 2005; Vourvachaki, 2009) emphasizes the productivity improvements/cost reductions that stem from the "direct" application of ICT (for example, the switch from mail to e-mail). The literature on the economics of telecommunications, in addition, argues that the use of these technologies can improve access to information. In line with Stigler (1961), this literature further argues that it would reduce distortions and frictions in the markets (e.g., Leff, 1984; Jensen, 2007; Brynjolfsson and Smith, 2000). Our empirical findings offer support for these conjectures. They imply that the diffusion of telecommunication technologies intensifies the competition in services and goods markets (i.e., reduces mark-ups). Meanwhile, given that the latter can matter for allocative and productive efficiency, our results suggest another driver behind the results of these macro- and micro-level empirical studies. In this respect, they also add to the suggestions of the literature on general ICT and indicate that the economic benefits from a particular type of ICT, telecommunication technologies, may come not only from direct use but also from intensified competition.[3]

The results of this study can be interesting also for policymakers. The results imply that policies that motivate higher use and wider adoption of telecommunication technologies can complement competition/antitrust policies.

Having mentioned what we identify in this study, it is also worth mentioning what

[2] Aghion et al. (2005) find an inverted-U shape relationship between the number of patents issued and the intensity of competition. Therefore, according to Aghion et al. (2005), our results imply higher innovative activity at least for lower levels of competition.

[3] Using growth accounting Oliner, Sichel, and Stiroh (2008) argue that the (direct) contribution of ICT to labor productivity growth in US industries has sharply declined recently. The authors also offer evidence that increased competitive pressures explain a significant portion of recent growth. In this respect, our results highlight the possible role of ICT in increased competitive pressures in US industries.

we do not intend to identify. The diffusion of telecommunication technologies can reduce some of the costs of entry. However, it is ultimately the corresponding changes in firms' and consumers' behavior that would affect the competition in services and goods markets. Given the data we have, we neither can nor intend to identify exactly how those changes would happen.

In addition to the literature on the economics of ICT and particularly on the economics of telecommunications, this paper is related to studies that try to identify the determinants of product market competition. Although competition seems to be an important engine of economic activity, to our best knowledge, there are very few such studies. There is evidence, for example, that railroad networks intensified competition in the US shipping industry in the 19th century (Holmes and Schmitz, 2001). There is also evidence that policies, including but not limited to those that intend to promote entry and competition, can affect the intensity of competition in various markets (see, for instance, Creusen, Minne, and van der Wiel, 2006; Feldkircher, Martin, and Wörz, 2010; Fisman and Allende, 2010). Our study is related to these studies to the extent that telecommunication technologies, similar to the railroad, are general purpose technologies. Moreover, according to our results, the policies that promote the diffusion of telecommunication technologies should affect the intensity of competition in services and goods markets.

There is also a vast amount of theoretical studies that analyze the effect of search frictions on price dispersion (see, for instance, Salop and Stiglitz, 1977; Varian, 1980). The typical model assumes that consumers know only the distribution of prices and have search costs. These costs are argued to be lower in electronic marketplaces compared to regular ones (Bakos, 1991). This motivates many empirical studies that try to find whether there is a significant difference in terms of price dispersion, as well as in term of average prices, between electronic and regular market places (e.g., Lee, 1998; Strader and Shaw, 1999; Brynjolfsson and Smith, 2000; Brown and Goolsbee, 2002). Our study is related to these papers to the extent that the diffusion of telecommunication technologies also can also lower consumers' search costs and these, together with price dispersion, can be related to the intensity of competition. In this respect, while these studies focus on particular markets (e.g., books, CDs, and life insurance) and market places, our inference is for (virtually) the entire economy.

The next section describes the theoretical background, motivates the methodology, and formally defines the objective of this study. The third section describes the data and their sources. The fourth section summarizes the results. The last section concludes. The tables of basic statistics, correlations, and regression results are presented at the end of the paper.

2.2 Theoretical Background and Methodology

How Telecommunications can Matter

The entry (and the potential entry) of firms can strengthen competition. It is often argued that information acquisition costs matter for firms' and entrepreneurs' decision to enter into a market (see Demsetz, 1982; Geroski, 1995b). For example, a firm which considers entry into a market would need to gather information about that market.

It seems that it is a common thought in the literature that the use of telecommunication technologies can reduce the information acquisition costs (e.g., see Leff, 1984; Norton, 1992; Röller and Waverman, 2001; Jensen, 2007; Czernich et al., 2011). A contemporary observation, which can support this argument is that these technologies enable internet, which in many cases can serve as a very cheap source of information.

Clearly, the decision of entry can be affected also by initial investment costs in infrastructure such as office equipment. The quote from *The Economist* suggests that the diffusion of telecommunication technologies can reduce these costs since it is cheaper to establish an online business. In turn, following Etro (2009), it can be argued that the diffusion of telecommunication technologies can reduce the initial investment costs in computer software and hardware. This can hold since telecommunication technologies support and enable cloud computing.

These arguments indicate that there can be a positive link between the diffusion of telecommunication technologies and the (potential) entry of firms. Therefore, they indicate that the diffusion can intensify the competition in services and goods markets which is in line with the conjectures of, for example, Freund and Weinhold (2004) and Czernich et al. (2011).[4] However, these arguments are certainly not conclusive. In this regard, it can be argued as well that the diffusion of telecommunication technologies can help firms gain market power. For example, it may help firms to increase product differentiation through the (extensive) advertisement of products over the internet and other types of telecommunication networks. Moreover, lower information acquisition costs can help firms to learn about the demand and the general market environment. Therefore, they can help to increase price discrimination and product differentiation. Such practices seem to be commonly applied in online as well as traditional firms (Taylor, 2004). Online firms, for example, can track via visited web sites, search keywords, and IP address the preferences and location of visitors and use that information for targeting their marketing appeals.

[4] Freund and Weinhold (2004) hypothesize that the diffusion of telecommunication technologies and, in particular, of internet can reduce the costs of entry. Further, they offer a stylized model, where the reduction of entry costs induces the entry of firms and increases the intensity of competition.

Methodology

Having contrasting arguments in hand, in this study, we try to identify the effect of the diffusion of telecommunication technologies on the competition in services and goods markets. Doing so is not straightforward, however. According to many theoretical models, the level of competition in services and goods markets matters for resource allocation in an economy. This in its turn can matter for the country-wide diffusion of telecommunication technologies, which is largely a market outcome. Therefore, there can be a reverse causality between the diffusion of telecommunication technologies and competition in the services and goods markets.

Nevertheless, there is a seemingly intuitive variation that can be used in order to alleviate the reverse causality concerns. The effect of the diffusion of telecommunication technologies on the costs of entry would be different for industries that depend more heavily on these technologies compared to industries that depend less. Such variation can arise because the industries that depend more heavily on telecommunication technologies *ceteris paribus* would increase their demand for these technologies more due to that diffusion. In turn, in line with the arguments offered in Leff (1984) or Jensen (2007), the increased demand can result in more information about the industry. An observation that supports these arguments is that telecommunication technologies are used exactly for transmitting and disclosing information. A further supporting observation is that nowadays, for instance, computer producers and retailers seem to be more widely known than the core manufacturers, when the former use significantly more of these technologies. According to these arguments the diffusion will alter the information acquisition costs disproportionately in industries that depend more heavily on telecommunication technologies. (In the Technical Appendix, we offer a very stylized and simplistic model that delivers predictions in line with our inference.)

Our test looks for exactly such a disparity. We test whether in countries where, *ex ante*, the diffusion of telecommunication technologies is higher, *ex post*, the level of product market competition is disproportionately different in industries that depend more on these technologies compared to the industries that depend less. One of the advantages of this test is that we need not explain the drivers behind the diffusion of telecommunication technologies, market or regulatory. In order for the diffusion to matter in such a setup, we need only to have a world where the diffusion cannot happen instantaneously or is costly. Either of these assumptions seems plausible given that the diffusion requires building infrastructure. Such a test also permits country and industry fixed effects. These can be important for capturing, for instance, regulatory differences and the variation in the fixed costs of entry into different industries. Moreover, with such a test, our inference would not depend on a particular country-level model of competition. This allows us to avoid using country-level variables, which often create ambiguities with the interpretation of the results. Instead, we focus on the varying effects of country-level variables across industries that are expected to be the most responsive to them.

To implement this test, our dependent variable is the level of product market competition in industry i and country c (averaged over the time/sample period). After controlling for industry and country fixed effects, in our empirical specification we should find that the coefficient on the interaction between the initial/*ex ante* level of the diffusion of telecommunication technologies and industries' dependence on those technologies is different from zero. In the empirical specification, we also control for the initial share of an industry in a country in total output (Industry Share), which can capture potential convergence effects. For instance, it can correct for the possibility that the larger industries in a country experience lower entry rates (Klapper, Laeven, and Rajan, 2006), which can affect the intensity of competition.

Our (baseline) empirical specification is then

$$\begin{aligned} \text{Competition}_{i,c} = \; & \alpha_{1,i} + \alpha_{2,c} \\ & + \alpha_3 \cdot (\text{Industry } i\text{'s Dependence} \times \text{The Diffusion in Country } c) \\ & + \alpha_4 \cdot \text{Industry Share}_{i,c} + \varepsilon_{i,c}, \end{aligned} \tag{2.1}$$

where $\varepsilon_{i,c}$ is the error term, and our focus is on the coefficient of the interaction term α_3. If we follow, for instance, Leff (1984) and Jensen (2007) and believe that cheaper information reduces the costs of entry, then we expect to have a positive α_3 (negative if we use an inverse measure for competition).

2.3 Measures and Data

We employ data for 21 countries from the European Union and focus on the period 1997–2006. We concentrate on this set of countries since we use the OECD STAN and Amadeus databases and want to focus on a somewhat coherent sample. We need these databases in order to construct the measures of competition, for instance. Particularly, we need the Amadeus database for constructing competition measures such as the Herfindahl index and the market share of the four largest firms, which require firm-level data and tend to be widely used both in the literature and by regulatory institutions. Although we could employ data starting from 1993, we do not do so since we have very few observations in the Amadeus database for the period 1993–1996. We could as well employ data until 2008, but we want to avoid incorporating data from the recent financial crisis.[5]

That we use data from a rather homogenous set of countries involves trade-offs. It can eliminate the influence of various unobservable factors on our inference, for example. However, at the same time it can weaken our inference from cross-country comparisons.

In order to estimate the specification, we need appropriate measures for the diffusion of telecommunication technologies, the level of industries' dependence on these technologies, and the competition in services and goods markets.

Measuring the Diffusion of Telecommunication Technologies

Our measure for the diffusion of telecommunication technologies (hereafter, telecom diffusion) is the number of fixed-lines and mobile telephone subscribers per capita (Telecom Subscribers).[6] This variable can indicate the adoption and use of telecommunication technologies in the entire economy and is extensively used in that context (e.g., Röller and Waverman, 2001).[7] This is important for us since potential entrepreneurs can use their personal/private telecommunications for acquiring information, while entrepreneurs and firms can use corporate ones. However, clearly at least some part of the use if measured in this manner will be hard to associate with the competition in goods and services markets. An example would be an uninformative discussion over the phone about weather. From this perspective, therefore, using this measure can play against us since it can bias our results towards zero.

We obtain the data for this measure from the ITU and GMID databases. Table 2.1 offers basic statistics for the main variables, which are described in detail in the Data Appendix (see Table A). Tables 2.6-2.11 in the Appendix - Further Results and Table B in the Additional Data Appendix offer correlations and basic statistics and descriptions of additional data.

Measuring the Dependence on Telecommunication Technologies

In a country, a naive measure of an industry's dependence on telecommunication technologies (hereafter, telecom dependence) would be its share of expenditures on telecommunications out of total expenditures on intermediate inputs. The problem with this

[5] The telecommunication services consumption patterns indicate strong differences between pre- and post-financial crisis periods, and no visible differences around the dot-com bubble period 1999–2001.

[6] Adding also internet subscribers can lead to significant double counting since, for example, fixed-lines are used extensively for dial-up and DSL internet. Nevertheless, we have checked that our results remain qualitatively the same if we use the per capita number of internet subscribers separately as a diffusion measure (see Table 2.12 in the Appendix - Further Results).

[7] Our results are qualitatively the same when we use, instead of this measure, the revenues of the telecommunications industry per capita which, in contrast, is a flow variable (see Table 2.12 in the Appendix - Further Results).

measure is that it reflects both the supply and the demand of those technologies when we need only the demand.

To alleviate this problem, as in the rest of the literature following Rajan and Zingales (1998), we try to identify the industries' dependence on telecommunication technologies from US data. This involves three important assumptions. The first and second are that in the United States the supply of telecommunication technologies is perfectly elastic and frictionless. The first assumption can be supported by the argument that the marginal cost of production in the telecommunications industry is very low. Meanwhile, the second can find support in the observation that the US has one of the most developed information and communication technologies sectors. Moreover, it tends to have exemplary regulations for the telecommunications industry and the lowest market prices for telecommunication services in the world. The third assumption is that the dependence identified from the US data also holds in other countries. More rigorously, we assume that there is some technological reason which creates variation in the industries' dependence on telecommunication technologies. Further, we assume that these technological differences persist across countries so that the dependence identified from the US data would be applicable for the countries in our sample.

These assumptions may seem to be rather strong. All we actually need, however, is that the rank ordering of the expenditure share on telecommunications in US industries corresponds to the rank ordering of the technological dependence of the industries. We need as well that rank ordering to carry over to the rest of the countries in our sample.

At least one argument can motivate why this rank ordering, perhaps together with the actual dependence level, can carry over to the rest of the countries. The share of expenditures on telecommunications is constant in a steady state equilibrium. Therefore, much of the variation within industries may arise from shocks that would change the relative demand for telecommunication technologies. An example of such a shock would be a factor-biased technological innovation. As long as, however, there is technological convergence across countries and these shocks are worldwide, our measure would be a valid proxy. From another perspective, if our measure is noisy, our findings may only suffer from attenuation bias.

Our most disaggregated data for the share of expenditures on telecommunications out of total expenditures on intermediate inputs in US industries are at the 2-digit industry level. We obtain these data from the input-output tables of the Bureau of Economic Analysis (BEA). The original data are in NAICS 2007 and have a time span 1993–2007. We transform these data to ISIC rev. 3.1 (hereafter, ISIC), in order to align them with the rest of our data and exclude the industries that are expected to have a large state involvement (80, 85, 90, and 91 of ISIC).[8] Further, we average these

[8]Our results are robust to their inclusion.

data over the period 1997–2006 and use the average as a measure for dependence.[9]

To gain more confidence about the validity of our measure, we perform a simple ANOVA exercise on our data for the share of expenditures on telecommunications out of total expenditures on intermediate inputs in US industries. This exercise shows that industry-level variation accounts for 99.48% of the total, and time variation accounts for only 0.52%, which provides support for the validity of our measure. Further, from the input-output tables from the OECD STAN database, we obtain the share of expenditures on telecommunications out of total expenditures on intermediate inputs in the industries from the European Union countries in our sample. These data have a structure similar to the 2-digit ISIC, though they are slightly more aggregated. Moreover, they are only for 1995, 2000, and 2005. We take the average of these three years and compute rank correlations between our dependence measure and these shares. The rank correlations are highly significant and range from 0.6 to 0.9 with a mean of 0.8, which provides further support for our measure (see Table 2.9 in the Appendix - Further Results).

Measuring Competition and Data for Industry Share

We use five measures of product market competition averaged over the period 1997–2006. These measures tend to be the most widely applied and/or theoretically robust.

Following Nickell (1996) and Aghion et al. (2005), our primary (inverse) measure of product market competition is the price cost margin (PCM). Under the assumption of constant marginal cost, it is the empirical analogue of the Lerner index. Therefore, it tends to be the reference competition measure and is widely applied in the recent empirical literature.

Using industry-level data, PCM is a weighted sum of Lerner indices in the industry across firms, where the weights are the market shares of the firms. In industry i, country c, and at time t, PCM is given by

$$PCM_{i,c,t} = \frac{(Revenue - Variable\ cost)_{i,c,t}}{Revenue_{i,c,t}},$$

where the variable costs include labor compensation and expenditures on intermediate inputs.[10]

[9] Our results remain qualitatively the same when we use expenditures on telecommunications relative to output (the so-called "technical coefficients") and the coefficients of inverse Leontief matrix as measures of dependence (see Table 2.12 in the Appendix - Further Results).

[10] We follow Collins and Preston (1969), Boone, Griffith, and Harrison (2005), and Oliner et al. (2008) while specifying PCM. In contrast, if we followed Aghion et al. (2005), we would have in the numerator net operating surplus minus financial costs. We do not prefer that measure since we have many fewer data for it. Meanwhile, it is highly correlated with our measure ($\rho = 0.7$), and our results are qualitatively the same with it.

Our second (inverse) measure for the intensity of competition is the profit elasticity (PE) introduced in Boone (2008). Profit elasticity captures the relation between profits and efficiency. This relation can be argued to become steeper as competition intensifies since in a more competitive environment the same percentage increase in costs reduces the profits more. In a given pair of industry and country and for all time periods, the PE is estimated using the following empirical specification:

$$\ln Profit_{f,t} = \beta_{1,f} + \beta_{2,t} + \beta_{3,t} \ln \left(\frac{Variable\ cost}{Revenue} \right)_{f,t} + \eta_{f,t}, \tag{2.2}$$

where f indexes firms, and $\eta_{f,t}$ is an error term. The PE in industry i, country c, and time t is the estimated coefficient $\hat{\beta}_{3,i,c,t}$.

The third and fourth (inverse) measures that we use are concentration measures. The third one is the Herfindahl index (HI), which is defined as the sum of the squared market shares of firms within an industry. Formally,

$$HI_{i,c,t} = \sum_{f=1}^{N_{i,c,t}} \left(\frac{Revenue_{f,i,c,t}}{\sum_{f=1}^{N_{i,j,t}} Revenue_{f,i,c,t}} \right)^2,$$

where N is the number of firms. The fourth one is the market share (MS) of the four largest firms in terms of revenues in each industry. Formally,

$$MS_{i,c,t} = \frac{\sum_{\tilde{f}=1}^{4} Revenue_{\tilde{f},i,c,t}}{\sum_{f=1}^{N_{i,c,t}} Revenue_{f,i,c,t}},$$

where $\tilde{f} = 1, 2, 3, 4$ are the four largest firms in industry i and country c at time t.

The fifth measure of competition is the number of firms in each industry, $N_{i,c,t}$. It may seem to be the most simplistic and disputable. It may relatively firmly approximate the intensity of competition in situations close to symmetric equilibrium.

Even though these measures are widely applied, in certain cases they may not fully reflect the intensity of product market competition. For instance, when the competition intensifies from more aggressive conduct, some firms may leave the market. In such a situation the Herfindahl index, being a concentration measure, can fail, suggesting that the intensity of competition has decreased. In the same situation a similar problem can arise with the market share of the four largest firms when, for instance, one or several of the largest firms leave the market.[11] Meanwhile, the price cost margin may fail in such a case when, for instance, inefficient firms leave the market. This would increase the weight of more efficient firms and, therefore, can increase the price cost margin (for

[11] Another possible criticism that applies to concentration measures such as MS and HI is that these are more tied to the geographic and product boundaries of the market in which the firms operate.

further discussion see Tirole, 1988). Given its definition, this problem is not present, however, in the measure of competition profit elasticity. Nevertheless, given that all our measures have a somewhat different nature (i.e., can reflect different forces behind the intensity of competition), it seems reasonable to use them for robustness checks of our results. It is worth noting also that averaging over time would alleviate some of these concerns since in such a case we focus on a rather long-term level of competition.

The data for the price cost margin and the number of firms we take from the OECD STAN database. We use the Amadeus database for the remaining measures of competition.

The Amadeus database has several features that need to be highlighted. First, in this database there is virtually no data for the financial intermediation and insurance and pension funding industries. Therefore, our analysis for competition measures from Amadeus does not contain those industries. Second, this database does not cover the universe of firms and may not have a representative sample. For instance, according to Klapper et al. (2006), it tends to overstate the percentage of large firms. This can affect the competition measures identified from that database.

Our industry and country fixed effects are likely to reduce such biases; nevertheless, we perform several robustness checks. Klapper et al. (2006) compare the data from Amadeus with data from Eurostat in terms of the within-industry distribution of the size of the firms and keep only the industries and countries which are sufficiently close to the data from Eurostat. We have checked that all our results hold for the sample of countries and industries which were employed in Klapper et al. (2006). We have also calculated the price cost margin from firm-level data from the Amadeus database and checked that all our results hold for the sample of countries and industries where this measure is sufficiently close to its OECD STAN counterpart (i.e., the squared percentage difference between two measures is less than its median in the entire sample).[12]

Finally, the share of an industry in a country in total (business) output in 1997 is obtained from the OECD STAN database.

2.4 Results

In column (1) of Table 2.2, we present our main results from the baseline specification (2.1), which we estimate using the least squares method. The dependent variable is our main (inverse) measure of intensity of product market competition, PCM, averaged over the period 1997–2006. Meanwhile, the interaction term consists of the logarithm of our telecom diffusion measure, Telecom Subscribers, in 1997 and the measure of dependence on telecommunication technologies, Telecom Dependence.

[12] We describe further that database and our data cleaning procedure in the Appendix - Data Cleaning.

The estimate of the coefficient on the interaction term is negative and significant at the 1% level [-2.72 (0.37)].[13] Given that smaller values of PCM correspond to higher competition intensity, this indicates that in industries that depend more on telecommunication technologies, competition is more intensive in countries with higher telecom diffusion. The diffusion of telecommunication technologies, therefore, has a positive effect on the intensity of competition in the services and goods markets.

Since we have a difference-in-differences estimate, one way to compute the magnitude of our result is as follows. We take the countries that rank in the 25th and 75th percentiles of the level of telecom diffusion and compute the difference between the logarithms of telecom diffusion levels. The countries are Estonia (25th) and France (75th) in our sample. Further, we take the industries that rank in the 25th and 75th percentiles of the level of dependence on telecommunication technologies and compute the difference between dependence levels. In our sample, these industries are Manufacture of Other Transport Equipment (25th) and Real Estate Activities (75th). Finally, we compute

$$\hat{\alpha}_3 \times \Delta \text{Telecom Dependence} \times \Delta \log \left(\text{Telecom Subscribers}\right),$$

where Δ stands for the difference operator between the 75th and 25th percentiles. The computed number is -0.020. This means that the difference in PCM (the intensity of competition) between Real Estate Activities and Manufacture of Other Transport Equipment is lower (higher) by 0.020 in France as compared to Estonia. This difference is relatively large compared to the mean of PCM, 0.190 (11%).

In an attempt to rule out other explanations for our main result, we conduct a range of robustness checks.

Robustness Checks

Alternative Measures for Competition

In order to check whether our results are robust in terms of the competition measure, we estimate our baseline specification (2.1) for the remaining four competition measures. Columns (2)-(5) in Table 2.2 report the results where, all else equal, the dependent variable is correspondingly the profit elasticity, the Herfindahl index, the market share of the four largest firms, and the logarithm of the total number of firms in an industry [-29.67 (12.47); -1.58 (0.54); -1.88 (0.62); and 17.05 (3.92)]. All the estimates of the coefficients on the interaction terms have the expected signs and are significant at least at the 5% level.

[13] The major part of the high R-squared is attributable to industry and country dummy variables.

We further report the estimation results exclusively for PCM. We have checked, however, that all our results stay qualitatively the same for the remaining measures of competition.

Alternative Measures for Dependence on Telecommunication Technologies

It could also be that our measure of dependence on telecommunication technologies fails to identify the ranking of industries correctly. This can happen, for example, when the shocks that create variation in our measure are not worldwide. Although according to the rank correlation tests, most likely, this is not the case, we perform robustness checks.

For a robustness check, we employ the shares of expenditures on telecommunications out of total expenditures on intermediate inputs in industries in Japan. This country tends to have a relatively well-developed ICT sector and relatively high telecommunication technologies diffusion. Therefore, it may be reasonable to expect that our assumptions are also valid for it. At the same time, it tends to have a different industrial composition than the United States, which would be another type of robustness check.

The data for this measure were obtained from the input-output tables from the OECD STAN database. These data are slightly more aggregated than the data for our main measure and are only for 1995, 2000, and 2005. We average the share of Japanese industries' expenditures on telecommunications over these three years and use it as a measure of dependence in our baseline specification (2.1).

Column (1) of Table 2.3 reports the results. The estimate on the interaction term is again negative, which reaffirms our main result. However, it is somewhat smaller in absolute value [-1.16 (0.22)]. In order to check this result, we calculate a measure of dependence using data from the OECD STAN database on US industries. With this measure the estimate of the coefficient on the interaction term is -1.65 (0.24), which is close to the estimate that we obtain using the measure identified from the data for Japan. Moreover, it is quite close to the main result although it implies a somewhat lower effect. It is different, however, since the OECD STAN database has a higher industry aggregation.[14]

In Column (3) of Table 2.3, we use as a measure of dependence the country-time average of the expenditure share on telecommunications in industries in our sample of EU countries. The estimate of the coefficient on the interaction term is not qualitatively different from the main one [-1.52 (0.35)].

[14] We have also estimated the specification (2.1) using the US measures for the overlapping sample of industries of the BEA and OECD STAN databases. The estimates are very close: -1.80 (0.30) and -1.09 (0.20), respectively.

We further report exclusively the results for our main measure of dependence on telecommunication technologies. We have, nevertheless, checked that all our results are qualitatively the same for these alternatives.

Non-parametric Estimator

In our difference-in-differences estimation, we essentially divide the countries into high diffusion (HDIFF) and low diffusion (LDIFF) and the industries into high dependence (HDEP) and low dependence (LDEP). Abstracting from the control variables, our estimate is

$$[\mathrm{HDEP(HDIFF)}-\mathrm{LDEP(HDIFF)}]-[\mathrm{HDEP(LDIFF)}-\mathrm{LDEP(LDIFF)}],$$

which captures the average effect only. The effect that we compute with this non-parametric estimator is -0.027. This result reassures us that the effect we have identified previously is generally present in all countries and industries.

Alternative Explanations: Varying Sample Restrictions

Time Period – Do we capture integration processes?

Further, we test whether our results are robust to various sample restrictions. First, we restrict our sample to 2000–2006 in order to check whether the integration processes in the European Union affect our results. Column (4) in Table 2.3 reports the results from the baseline specification. The dependent variable is PCM and, together with the measure of telecom dependence, it is averaged over the period 2000–2006. The measure of telecom diffusion and the industry share variable are from 2000. The estimate of the coefficient on the interaction term is negative and highly significant [-3.21 (0.55)].[15] Its magnitude has increased in comparison with the main results, but not considerably. This suggests that the integration processes are not likely to be the drivers behind our results.

Country-level – Are new EU member countries different?

The former transition countries the Czech Republic, Slovakia, Estonia, Slovenia, Poland, and Hungary, which joined the EU in 2004, can be different from the remaining countries in our sample. In these countries, the privatization process has resulted in the emergence of a large number of private firms (Klapper et al., 2006). Moreover, these

[15] Our results are virtually the same if we consider the periods 1998–1999 and 1996–2005. Our results also do not change when we add to our specification the interaction between Telecom Dependence and the ratio of imports and exports to GDP, which can capture integration processes. Similarly, they do not change when we add the interaction between Telecom Subscribers and the ratio of industry-level imports and exports to output (we obtain the data for imports and exports from OECD STAN and OECD Stat).

countries have gone through large structural/industry changes. The latter can affect the intensity of competition, whereas the former can affect the patterns of telecommunication technologies use. We want to make sure that our results are not driven by these factors.

Column (5) in Table 2.3 reports the results when we exclude these countries from the sample [-3.55 (0.83)]. It also reports on the Chow test for the equality of coefficients on the interaction terms for these countries and the remaining countries in our sample (p-value: 0.15).

We further check whether sectorial or industry differences drive or affect our results.

Sector/Industry-level – Are the services industries different?

The processes behind our results may be different in the services industries compared to the goods/manufacturing industries. This is because services products can be more easily marketed and delivered over telecommunication networks. Therefore, in line with the literature on electronic versus regular market places, it might be reasonable to expect that the role of the consumers' search costs is different for these industries. These costs can be important since they can affect the intensity of competition (e.g., Bakos, 1991). Although theory does not have a clear-cut inference, empirical studies seem to point out that the relationship is likely to be negative (e.g., Brynjolfsson and Smith, 2000; Brown and Goolsbee, 2002).

Column (6) of Table 2.3 reports the results when we restrict the sample to the services industries. The estimate of the coefficient is essentially the same as our main estimate [-3.00 (0.61)]. In turn, the simple Chow test suggests that there is no significant difference between the services and the goods industries.

Sector/Industry-level – Are those that use telecommunications the least different?

We have also checked that our results are not qualitatively different from the main result for the industries that, most likely, affect telecom diffusion the least. In order to identify such industries, we take the interaction between the variables Industry Share and Telecom Dependence and for a country take those industries that have a value lower than the median in that country.

Column (7) of Table 2.3 reports the results. The coefficient for the industries that have lower-than-median interaction between Telecom Dependence and Industry Share is essentially the same as our main result [-2.97 (1.74)]. This exercise suggests that our results are not likely to be driven by reverse causality. Nevertheless, we continue to explore such a possibility.

Alternative Explanations: Reverse Casuality

Instrumental Variables

Our inference would be incorrect if a third factor is responsible for the intensity of competition and is correlated with the interaction between dependence and diffusion measures. In this section, we attempt to rule out such an explanation of our results.

First, we try to alleviate further the reverse causality concerns and instrument the pre-determined level of the diffusion of telecommunication technologies. The set of instruments that we use consists of dummy variables for country groups: countries that joined the EU in 2004 (new members of the EU), Scandinavian countries, and France-Germany. The first set of countries inherited their (antiquated) telecommunications infrastructure from their socialist regimes. Scandinavian countries, in turn, were very effective in promoting universal access via state control and subsidies after deregulation (e.g., Gruber and Verboven, 2001). Meanwhile, France and Germany had the best access to mobile technologies through industry leaders such as La Compagnie Générale d'Électricité and Siemens. Column (1) in Table 2.4 reports the results [-2.78 (0.40); first stage F-stat p-value: 0.00]. They are no different from our main results.

Our country-group-level instrumental variables may not solve the endogeneity problem, however. It might be that they are correlated with some omitted variables and therefore do not satisfy the exclusion restrictions.

Omitted Variables – Do we identify other costs of entry?

According to, for example, Klapper et al. (2006), the country groups that comprise our instruments are quite different in terms of variables that matter for entry (and potential entry) and for the size distribution of firms and, thus, for the intensity of competition. Following Klapper et al. (2006) and Scarpetta, Hemmings, Tressel, and Woo (2002), these variables are the bureaucratic costs of entry, product market regulation, financial development, the regulation of labor, property rights, and human capital development (or the availability of qualified personnel). To the extent that the diffusion of telecommunication technologies is correlated with these variables (e.g., because it reflects the business environment), and the rank of telecom dependence is correlated with the rank of the industries that are mostly affected by these variables, our inference would be incorrect.

We follow the literature to find measures for these country-level variables and to identify the ranking of industries according to the effect these variables should have on them (i.e., on the competition in those industries).

A. Measures for Country-level Variables

We obtain the measure and the data for the bureaucratic costs of entry from Djankov, La Porta, Lopez-de-Silanes, and Shleifer (2002). These costs include all identifiable official expenses in a country. To measure the country-wide market regulation, we use the product market regulation indicator from OECD Stat. This indicator takes into account the public control of business, bureaucratic barriers to entrepreneurship, trade, and investment. Higher values stand for higher product market regulation. We measure the level of financial development as stock market capitalization over GDP. We take the data from the WDI database. The measure and data for the regulation of labor we obtain from Botero, Djankov, La Porta, Lopez-de-Silanes, and Shleifer (2004). This is an index that takes into account job security, the conditions of employment, and the provisions in laws regarding alternative employment contracts. Higher values mean higher protection for a worker. Further, to proxy property rights and their enforcement, we use the property rights index constructed by the Heritage Foundation. It measures the protection of private property in a country. Higher values stand for higher private property protection. Given availability, the data for these measures are for 1999, 1997, 1997, 1998, and 1997 respectively. Finally, as a measure of human capital development, we use the average years of schooling for the population older than 25. The data are for 1995, and we obtain them from the Barro-Lee tables, the World Bank.

B. Identifying the Ranking of the Industries According to the Effect

The bureaucratic costs of entry, according to Klapper et al. (2006), have a higher impact on entry in "naturally" high-entry industries. It would be reasonable to expect that product market regulation matters in these industries in a similar way. Meanwhile, financial development, according to Rajan and Zingales (1998), has a higher impact on the creation of new establishments in industries that depend more on external finance. The strictness of labor regulation, in turn, could be expected to have a disproportionate impact on the industries that have high labor intensity. Further, property rights and human capital development would have a disproportionate impact on the industries that have high R&D intensity.

We use the measure and the data of Klapper et al. (2006) to identify the naturally high-entry industries. It is defined as the percentage of new corporations (firms that are no older than one year) in an industry in the US, and it is averaged over the period 1998–1999 in that paper. We take the measures and the data for dependence on external finance and R&D intensity from Bena and Ondko (2012). The first is defined as the industry median of the average of the ratio of capital expenditures minus cash flows from operations to capital expenditures over the period 1996–2005. Meanwhile, R&D intensity is defined as the industry median of the ratio of averages of R&D expenditures to capital expenditures over the period 1996–2005. As a measure for labor intensity we use the ratio of the number of employees to output in US industries averaged over the period 1997–2006. We take these data from the OECD STAN database.

C. Answering the Question

In order to check whether any of these variables matter for our results, we create an interaction term and add it to the baseline specification (2.1). Columns (2)-(7) of Table 2.4 report the results. Clearly, the fact that we use data for the years 1999 and 1998 for bureaucratic costs of entry and market regulation can raise further endogeneity concerns. To alleviate these concerns, we have checked that our results are no different when we use data for competition, dependence, and diffusion measures from the period 2000–2006, for example.

The coefficient on the interaction term between the measures of dependence and diffusion remains virtually the same in all cases. It somewhat, though, reduces in absolute value when we insert the interaction between measures of labor regulation and labor intensity, column (5). However, this effect is neither significant nor driven by that interaction term. The estimate of the baseline regression on the sub-sample where we have values for the latter interaction term is virtually the same.

Generally, the signs of the coefficients of additional interaction terms are intuitive, although the estimates are not significant. For instance, higher bureaucratic costs of entry and stricter market regulation are likely to hinder entry (and potential entry) in naturally high-entry industries. Therefore, they might reduce the intensity of competition in these industries. The strictness of labor regulation can reduce the future expected value of the entrant more in labor-intensive industries. Therefore, it may hinder entry (and potential entry) and competition in such industries. The respective estimates are correspondingly positive. The estimates of the coefficients on interaction terms for the financial development measure and the property rights index are also positive. A possible explanation for this is that the incumbents use, for example, patent protection and finance for deterring entry and/or escaping competition. Meanwhile, the negative coefficient on the interaction term for the level of human capital most likely suggests that the availability of qualified personnel reduces entry costs in R&D intensive industries. Exploring these conjectures is well beyond the scope of this study.[16]

All these additional interaction terms, as well as our main interaction term, may proxy for the business environment in the country. Another rough way to proxy for that, together with the entrepreneurial culture in the country, is to include an interaction term of the Telecom Dependence variable with the average intensity of competition for the country. Column (1) of Table 2.5 reports the result when we include such an

[16]It might also be argued that the ranking of the industries according to their dependence on telecommunication technologies corresponds to the ranking of industries according to the effect these variables have on them. In Table 2.14 in the Appendix - Further Results, we explore this hypothesis. In that table, we also report the results when in addition to our main interaction term we include the interaction of Telecom Dependence with a market regulation indicator for the telecommunications industry.

interaction term in our baseline specification [-2.80 (0.39)].

Omitted Variables – Does our measure of dependence simply identify the growth potential of the industries?

It could also be that the measure of dependence on telecommunication technologies identifies the industries that have high growth potential. Meanwhile, such industries could depend on the availability of modern technologies, which might be proxied by the diffusion of telecommunication technologies, and face tougher competition due to attractiveness.

In order to measure the growth potential of the respective industries, following Fisman and Love (2007), we use the growth rate of output of US industries averaged over the period 1998–2007. We obtain these data from the output figures taken from the Bureau of Economic Analysis. This measure seems to be the most appropriate given the relatively low market imperfections in the United States. However, it could fail if there are important taste differences in the US compared to our sample countries. Therefore, we also use the growth rates of output of industries in the three most developed (measured by GDP per capita in 1997) EU countries in our sample averaged over the countries and the 1998–2007 period.

We interact the measures of growth potential with the measure of diffusion of telecommunication technologies, Telecom Subscribers, and include the interactions in the baseline specification. Columns (2) and (3) of Table 2.5 report the results. The estimate of the coefficient on the interaction between Telecom Dependence and Telecom Subscribers stays virtually unaffected. The estimated coefficients on the interactions between Telecom Subscribers and the measures of growth potential are negative. This suggests that in countries where the diffusion of telecommunication technologies is higher, the competition is more intensive in industries with higher growth potential. An explanation for this can be that industries with high growth potential depend more on such (modern) technologies (see Table 2.11 in the Appendix - Further Results for the correlation between the measures of growth potential and dependence on telecommunication technologies). Therefore, a higher diffusion of telecommunication technologies reduces (potential) entry costs in these industries more than in low growth potential industries.

As a final check, we also include in our baseline specification the growth rates of industries in the EU countries in our sample averaged over the period 1998–2007. We report the result in column (4) of Table 2.5. Our main result stays virtually unaffected [-2.37 (0.47)]. Our main result also stays unaffected if we include all these additional terms at once, but these results are not reported. (In the Appendix - Further Results, we offer results from further robustness check exercises, see Tables 2.12-2.15.)

2.5 Conclusions

In this study, we use industry-country-level data in order to identify the effect of the wider adoption and more intensive use (diffusion) of telecommunication technologies on the competition in services and goods markets. Taken together, our results offer a robust inference that the diffusion of telecommunication technologies significantly intensifies competition. It does so especially in the industries that depend more on these technologies.

According to the theory and empirical evidence, the intensity of product market competition matters for allocative and productive efficiency. Therefore, our empirical results highlight a mechanism for how the use of a particular type of ICT, telecommunication technologies, can contribute to economic performance. This complements, for example, the productivity improvement mechanism that tends to be extensively emphasized in the literature.

Our results also suggest that the policies intended to promote the diffusion of telecommunication technologies can complement competition policies.

Tables

Table 2.1: *Summary Statistics*

Variable	Obs.	Mean	SD	Min.	Max.
Country-level					
Bureaucratic costs of entry in 1999 [B.Entry Cost]	20	0.19	0.20	0.01	0.86
Business environment in 1997 [Business Environment]	21	0.19	0.02	0.15	0.23
Telecommunications subscribers per capita in 1997 [Telecom Subscribers]	21	0.61	0.23	0.22	1.06
Financial development in 1997 [Financial development]	21	0.28	0.23	0.02	0.79
Human capital development level in 1995 [Human Capital]	21	9.48	1.28	6.82	11.45
Product market regulation in 1998 [Market Regulation]	18	2.25	0.65	1.07	3.97
Property rights regulation in 1997 [Property Rights]	21	0.77	0.13	0.50	0.90
Regulation of labor in 1997 [Labor Regulation]	20	0.61	0.15	0.28	0.81
Industry-level					
Alternative growth potential indicator 1998–2007 [Growth Potential EU]	47	0.05	0.05	-0.06	0.22
Alternative telecom dependence indicator using data from Japan 1995–2005 [Telecom Dependence JP]	30	0.02	0.02	0.00	0.09
Alternative telecom dependence indicator using OECD data for US 1995–2005 [Telecom Dependence OECD]	30	0.02	0.02	0.00	0.10
Alternative telecom dependence indicator using EU data 1995–2005 [Telecom Dependence EU]	30	0.02	0.02	0.00	0.08
Entry rates in the US industries 1998–1999 [Entry Rate]	44	6.15	1.76	1.74	10.73
External finance dependence 1996–2005 [Ext. Fin. Dependence]	46	0.32	0.72	-1.55	2.95
Growth potential 1998–2007 [Growth Potential]	47	0.01	0.03	-0.09	0.09
Labor intensity 1997–2006 [Labor Intensity]	24	0.01	0.00	0.00	0.02
R&D intensity 1996–2005 [R&D Intensity]	46	0.70	1.16	0.00	4.17
Telecom dependence 1997–2006 [Telecom Dependence]	47	0.01	0.02	0.00	0.06
Industry-country-level					
Herfindahl index 1997–2006 [HI]	928	0.14	0.17	0.00	1.00
Logarithm of the number of firms 1997–2006 [logN]	863	7.24	2.63	1.39	13.49
Market share of four largest firms 1997–2006 [MS]	928	0.45	0.27	0.02	1.00
Output growth 1998–2007 (real) [Average Growth]	788	0.05	0.07	-0.61	0.48
Price cost margin 1997–2006 [PCM]	902	0.19	0.13	0.01	0.89
Profit elasticity 1997–2006 [PE]	892	-5.29	3.47	-20.56	-0.03
Share of industry in industrial output in 1997 [Industry Share]	926	0.02	0.03	0.00	0.24

Note: This table reports basic statistics for the key variables used in the paper. All variables and data sources are defined in detail in Table A in the Data Appendix.

Table 2.2: *The Main Result and the Results for Alternative Competition Measures*

	(1) PCM	(2) PE	(3) HI	(4) MS	(5) logN
Telecom Dependence	-2.66***	-29.67**	-1.58***	-1.88***	17.05***
× Telecom Subscribers	(0.37)	(12.47)	(0.54)	(0.62)	(3.92)
Industry Share	0.69***	17.35***	-0.25	-0.59*	10.55***
	(0.26)	(4.81)	(0.21)	(0.34)	(2.15)
Observations	902	844	876	876	818
R2	0.72	0.52	0.59	0.73	0.93

Note: This table reports the results from the baseline specification (2.1) for all our measures of product market competition. All measures are averaged over the period 1997–2006. See Table A in the Data Appendix for complete definitions and sources of variables. All regressions include industry and country dummies and use the least squares estimation method. Robust standard errors are in parentheses. *** indicates significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table 2.3: *Alternative Measures of Dependence and Different Samples*

	(1) JP	(2) (OECD)	(3) EU	(4) 2000-2006 sample	(5) W/o New EU Members	(6) Services	(7) Least Telecom User
Telecom Dependence [ ]	-1.16***	-1.65***	-1.52***				
× Telecom Subscribers	(0.22)	(0.24)	(0.35)				
Telecom Dependence				-3.21***	-3.55***	-3.00***	-2.97*
× Telecom Subscribers				(0.55)	(0.83)	(0.61)	(1.74)
Chow test (p-value)					0.15	0.38	0.99
Industry Share	0.77**	0.82***	0.82***	0.72**	0.67**	0.68*	-0.47
	(0.31)	(0.31)	(0.31)	(0.29)	(0.28)	(0.37)	(0.40)
Observations	618	618	618	900	637	411	461
R2	0.75	0.75	0.75	0.71	0.70	0.68	0.58

Note: This table reports the results from the baseline specification (2.1) for various measures of dependence on telecommunication technologies and sample restrictions. The dependent variable is PCM. It is averaged over the period 2000–2006 in column (4) and over the period 1997–2006 in the remaining columns. In columns (1)-(3) we vary the dependence measure. In columns (1) and (2), the measures of dependence are identified from OECD STAN data for Japan and the US. In column (3), the dependence measure is constructed as the average of an industry's share of expenditures on telecommunications out of total expenditures on intermediate inputs in all EU countries from our sample. The data are from the OECD STAN database. All measures of dependence from the OECD STAN database are averaged over the years 1995, 2000, and 2005. In column (4), Telecom Subscribers and Industry Share are for 2000 and Telecom Dependence is averaged over the period 2000–2006. In column (5), New EU Members (the Czech Republic, Estonia, Hungary, Poland, Slovakia, and Slovenia) are excluded from the sample. Column (6) excludes the goods industries. Column (7) excludes the industries in a country that have a higher-than-median Telecom Dependence times Industry Share in the country. For samples in columns (5)-(7) we perform Chow tests for the coefficients on the interaction terms. The p-values of corresponding t-statistics are reported in the row Chow test. See Table A in the Data Appendix for complete definitions and sources of variables. All regressions include industry and country dummies and use the least squares estimation method. Robust standard errors are in parentheses. *** indicates significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table 2.4: *Specification Check - IV and Additional Variables*

	(1) IV	(2) B.Entry Cost	(3) Market Regulation	(4) Financial Development	(5) Labor Regulation	(6) Property Rights	(7) Human Capital
Telecom Dependence	-2.78***	-2.67***	-3.05***	-2.93***	-1.68***	-2.90***	-2.91***
× Telecom Subscribers	(0.40)	(0.41)	(0.52)	(0.36)	(0.32)	(0.36)	(0.36)
Entry Rate		0.01					
× B.Entry Cost		(0.01)					
Entry Rate			0.00				
× Market Regulation			(0.00)				
Ext. Fin. Dependence				0.02			
× Financial Development				(0.02)			
Labor Intensity					2.33		
× Labor Regulation					(5.25)		
R&D Intensity						0.00	
× Property Rights						(0.01)	
R&D Intensity							-0.02
× Human Capital							(0.02)
Industry Share	0.67***	0.75***	0.83***	0.69***	0.74***	0.70***	0.73***
	(0.25)	(0.26)	(0.27)	(0.27)	(0.23)	(0.27)	(0.27)
Observations	902	803	721	882	462	882	882
R2	0.72	0.73	0.71	0.73	0.84	0.73	0.73

Note: In regressions reported in this table, the dependent variable is the competition measure PCM averaged over the period 1997–2006. Column (1) reports the results from the baseline specification, which we estimate using instrumental variable techniques (GMM 2S). The instrumental variables are dummy variables for country groups: countries that joined the EU in 2004 (the new members of the EU), Scandinavian countries (Denmark, Norway and Sweden), and France and Germany. Columns (2)-(7) report the results from specifications that augment the baseline with additional interaction terms. See Table A in the Data Appendix for complete definitions and sources of variables. All regressions include industry and country dummies and in columns (2)-(7) use the least squares estimation method. Robust standard errors are in parentheses. *** indicates significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table 2.5: *Specification Check - Additional Variables*

	(1) Business Environment	(2) Growth Potential	(3) Growth Potential EU	(4) Average Growth
Telecom Dependence × Telecom Subscribers	-2.80***	-2.24***	-2.57***	-2.37***
	(0.39)	(0.43)	(0.37)	(0.47)
Telecom Dependence × Business Environment	13.06			
	(8.80)			
Growth Potential × Telecom Subscribers		-0.36**		
		(0.16)		
Growth Potential EU × Telecom Subscribers			-0.43***	
			(0.12)	
Average Growth				0.11***
				(0.04)
Industry Share	0.69***	0.68**	0.68***	0.93**
	(0.26)	(0.27)	(0.26)	(0.38)
Observations	902	902	902	783
R2	0.72	0.72	0.72	0.73

Note: This table reports the results from specifications that augment the baseline with additional interaction terms. The dependent variable is the competition measure PCM averaged over the period 1997–2006. See Table A in the Data Appendix for complete definitions and sources of variables. All regressions include industry and country dummies and use the least squares estimation method. Robust standard errors are in parentheses. *** indicates significance at the 1% level, ** at the 5% level, and * at the 10% level.

Appendix

Data Appendix

Table A: *Definitions and Sources of Variables*

Variable Name	Definition and Source
Country-level Variables	
B.Entry Cost	The bureaucratic cost of obtaining legal status to operate a firm as the share of per capita GDP in 1999. Source: Djankov et al. (2002).
Business Environment	PCM averaged over industries in 1997. Source: Authors' calculations using data from OECD STAN.
Financial Development	The ratio of stock market capitalization to GDP in 1997. Source: WDI.
Human Capital	The average years of schooling of the population 25 years of age or over. The data are for 1995. Source: Barro-Lee tables, World Bank.
Labor Regulation	Index of labor regulations in 1997. This index takes into account job security, the conditions of employment, and the provisions in laws regarding alternative employment contracts. Source: Botero et al. (2004).
Market Regulation	Product market regulation indicator in 1998. This indicator takes into account the public control of business, bureaucratic barriers to entrepreneurship, trade, and investment. Source: OECD Stat.
Property Rights	Property rights index in 1997. This index measures the protection of private property in a country. Source: The Heritage Foundation.
Telecom Subscribers	The sum of fixed-line and mobile telephone subscribers per capita, in 1997. Source: Authors' calculations using data from ITU and GMID.
Industry-level Variables	
Entry Rate	The percentage of new corporations (firms that are not more than one year old) in US industries, averaged over the period 1998–1999. Source: Klapper et al. (2006) using Dun & Bradstreet.
Ext. Fin. Dependence	The median of the ratio of capital expenditures minus cash flow from operations over capital expenditures in US industries (where both are averaged over the period 1996–2005 for a firm). Source: Bena and Ondko (2012) using Compustat.
Growth Potential	The annual growth rate of real output of US industries, averaged over the period 1998–2007. Source: Authors' calculations using data from BEA.
Growth Potential EU	The annual growth rate of real output of industries from the three most developed EU countries in terms of real GDP per capita in 1997, averaged over the countries and the period 1998–2007. Source: Authors' calculations using data from OECD STAN.
Labor Intensity	The ratio of number of employees to production (in $1000) in US industries, averaged over the period 1997–2006. Source: Authors' calculations using data from OECD STAN.
R&D Intensity	The ratio of median R&D expenditures over median capital expenditures in US industries. Both components are averaged over the period 1996–2005. Source: Bena and Ondko (2012) using Compustat.
Telecom Dependence	The share of (real) expenditures on telecommunications out of total expenditures on intermediate inputs in US industries, averaged over the period 1997–2006. Source: Authors' calculations using data from BEA, I-O tables.

Table A – (Continued)

Variable Name	Definition and Source
Telecom Dependence EU	The share of (real) expenditures on telecommunications out of total expenditures on intermediate inputs in industries in EU countries from our sample, averaged over countries and the years 1995, 2000 and 2005. Source: Authors' calculations using data from OECD STAN, I-O tables.
Telecom Dependence JP	The share of (real) expenditures on telecommunications out of total expenditures on intermediate inputs in industries in Japan, averaged over the years 1995, 2000 and 2005. Source: Authors' calculations using data from OECD STAN, I-O tables.
Telecom Dependence (OECD)	The share of (real) expenditures on telecommunications out of total expenditures on intermediate inputs in US industries, averaged over the years 1995, 2000 and 2005. Source: Authors' calculations using data from OECD STAN, I-O tables.
Industry-country-level Variables	
Average Growth	The annual growth rate of real output of industries from EU countries in our sample, averaged over the period 1998–2007. Source: Authors' calculations using data from OECD STAN.
HI	Herfindahl index, averaged over 1997–2006. This index is defined as the sum of squared market shares of firms within an industry. Source: Authors' calculations using data from Amadeus.
Industry Share	The ratio of output in an industry in a country to the total (business) output in the country in 1997. Source: Authors' calculations using data from OECD STAN.
Least Telecom Users	Dummy variable that takes value 1 for a industry-country pair if the interaction between Industry Share and Telecom Dependence is lower than the median in the country, and zero otherwise. Source: Authors' calculations using data from OECD STAN and BEA.
logN	The logarithm of the number of firms in an industry, averaged over 1997–2006. Source: OECD STAN.
MS	Market share of the four largest firms in an industry, averaged over 1997–2006. Source: Authors' calculations using data from Amadeus.
PCM	Price cost margin is computed as revenue (sales) minus intermediate cost and labor costs divided by sales, averaged over 1997–2006. Source: Authors' calculations using data from OECD STAN.
PE	Profit elasticity in an industry-country pair is the estimate of the coefficient β_3 in the empirical specification (3), averaged over 1997–2006. Source: Authors' calculations using data from Amadeus.

Country Sample:

Austria, Belgium, the Czech Republic[1], Denmark[2], Estonia[1], Finland, France, Germany, Greece, Hungary[1], Ireland, Italy, the Netherlands, Norway[2], Poland[1], Portugal, Slovakia[1], Slovenia[1], Spain, Sweden[2], and the UK. ([1] new EU member countries; [2] 3 most developed EU countries in terms of GDP per capita in 1997.)

Industry sample (ISIC rev. 3.1):

10, 11, 13-36, 40, 41, 45, 50-52, 55, 60-63, 65-67, 70-74, 92, and 93. (Industries 65-67 are not in the sample for competition measures constructed using Amadeus data. In OECD STAN data, industries 10-14, 15-16, 17-19, 21-22, 36-37, 40-41, 50-52, 60-63, and 65-67 are merged. Further, these data do not contain industries 92 and 93.)

Technical Appendix

A very stylized and simplistic model that delivers predictions in line with our inference is as follows. Assume that there are two industries which produce differentiated goods $\{x_1\}$ and $\{x_2\}$. Further, consumption good (Y) is produced with a Cobb-Douglas production technology,

$$Y = \lambda_Y X_1^{\sigma_1} X_2^{\sigma_2}, \tag{2.3}$$

where $\sigma_1 + \sigma_2 = 1$, $\lambda_Y > 0$, and X_1 and X_2 are Dixit-Stiglitz aggregates of the goods produced in these industries,

$$X_i = \left(\sum_{f=1}^{N_i} x_{i,f}^{\frac{\varepsilon_i - 1}{\varepsilon_i}} \right)^{\frac{\varepsilon_i}{\varepsilon_i - 1}}, i = 1, 2. \tag{2.4}$$

Here i indexes the industries, N stands for the number of firms, f indexes the firms, and ε is the (actual) elasticity of substitution between the products of the firms in these industries ($\varepsilon > 1$).

Normalizing aggregate demand to 1 and taking the consumption good as the numeraire, it follows that the demand for $x_{i,j}$ is

$$p_{x_{i,j}} x_{i,j} = \sigma_i \frac{x_{i,j}^{\frac{\varepsilon_i - 1}{\varepsilon_i}}}{\sum_{f=1}^{N_i} x_{i,f}^{\frac{\varepsilon_i - 1}{\varepsilon_i}}}, \tag{2.5}$$

where p_x is the price of x.

Further, assume that x_1 and x_2 are produced using telecommunication technologies (T) and some other good (L) with Cobb-Douglas production technologies,

$$x_i = \lambda_i T_i^{\alpha_i} L_i^{1-\alpha_i}, \tag{2.6}$$

where $\lambda > 0$ and $\alpha_1 > \alpha_2$: Industry 1 depends on telecommunication technologies more than industry 2. For simplicity, let the firms live for one period. Meanwhile, the entrants pay a fixed cost F_i for entry into the respective industry, and there is free entry into the industries (where $F_i < \frac{\sigma_i}{\varepsilon_i}$ for $i = 1, 2$ since aggregate demand is equal to 1). In order to cover the costs of entry, these firms set prices. In an industry each firm internalizes its effect on the demand for the goods of the remaining firms in the industry.

The problem of firm j in industry i is

$$\max_{T_{i,j}, L_{i,j}} \pi_{i,j} = p_{x_{i,j}} x_{i,j} - p_T T_{i,j} - p_L L_{i,j} - F_i \tag{2.7}$$
$$s.t.$$

$$(2.5),$$

where p_T and p_L are the prices of T and L. Therefore, firm j's demands for T and L are given by

$$p_T = p_{x_{i,j}} \left(1 - \frac{1}{e_{i,j}}\right) \frac{\partial x_{i,j}}{\partial T_{i,j}}, \tag{2.8}$$

$$p_L = p_{x_{i,j}} \left(1 - \frac{1}{e_{i,j}}\right) \frac{\partial x_{i,j}}{\partial L_{i,j}}, \tag{2.9}$$

where $e_{i,j}$ is firm j's perceived elasticity of substitution between goods in its industry

$$e_{i,j} = \varepsilon_i \left[1 + (\varepsilon_i - 1) \frac{x_{i,j}^{\frac{\varepsilon_i - 1}{\varepsilon i}}}{\sum_{f=1}^{N_i} x_{i,f}^{\frac{\varepsilon_i - 1}{\varepsilon_i}}}\right]^{-1}.$$

In this framework competitive pressure in an industry can be expressed in terms of the Lerner index (LI). For firm j from industry i this index can be derived from (2.6), (2.8), and (2.9) setting $x_{i,j} = 1$. It is given by

$$LI_{i,j} = \frac{1}{e_{i,j}}.$$

Ceteris paribus, in an industry it declines with actual elasticity of substitution ε and the number of firms N.

Assuming symmetric equilibrium in each of the industries, the perceived elasticity of substitution is given by

$$e_i = \frac{\varepsilon_i}{1 + \frac{\varepsilon_i - 1}{N_i}}.$$

In turn, the demands for T and L in each industry can be written as

$$N_i p_T T_i = \sigma_i \alpha_i \left(1 - \frac{1}{e_i}\right), \tag{2.10}$$

$$N_i p_L L_i = \sigma_i (1 - \alpha_i) \left(1 - \frac{1}{e_i}\right). \tag{2.11}$$

Given that there is free entry, the number of firms in each industry is determined by a zero profit condition $\pi_i = 0$. Using (2.5), (2.7), (2.10), and (2.11) it can be easily shown that this condition is equivalent to

$$\sigma_i \frac{1}{N_i} = \sigma_i \left(1 - \frac{1}{e_i}\right) \frac{1}{N_i} + F_i.$$

Therefore, the number of firms in each industry is

$$N_i = \frac{\frac{\sigma_i}{\varepsilon_i} + \sqrt{\left(\frac{\sigma_i}{\varepsilon_i}\right)^2 + 4F_i\sigma_i\frac{\varepsilon_i - 1}{\varepsilon_i}}}{2F_i}. \tag{2.12}$$

From this expression, it is straightforward to show that the number of firms N in each industry declines with entry cost F. This implies that decreasing entry cost F in industry i reduces LI_i or, equivalently, increases competition. After tedious algebra, it is also possible to show that increasing elasticity of substitution ε in industry i reduces LI_i or, equivalently, increases competition.

In turn, allocations of T and L can be solved using (2.10), (2.11), and market clearing conditions:

$$\begin{aligned} N_1T_1 + N_2T_2 &= T, \\ N_1L_1 + N_2L_2 &= L. \end{aligned}$$

These allocations are given by

$$\begin{aligned} N_iT_i &= \frac{1}{1 + \frac{\alpha_{-i}}{\alpha_i}\frac{\sigma_{-i}}{\sigma i}\left(1 - \frac{1}{e_{-i}}\right)\left(1 - \frac{1}{e_i}\right)^{-1}}T, \\ N_iL_i &= \frac{1}{1 + \frac{1-\alpha_{-i}}{1-\alpha_i}\frac{\sigma_{-i}}{\sigma_i}\left(1 - \frac{1}{e_{-i}}\right)\left(1 - \frac{1}{e_i}\right)^{-1}}L. \end{aligned}$$

Let industries have equal shares ($\sigma_i \equiv \sigma$), then increasing T increases N_1T_1 more than N_2T_2. Following, for example, Geroski (1995b) and Leff (1984) and assuming that $F_i = F_i(N_iT_i)$ and $F_i' < 0$ implies that N_1 increases more than N_2. Therefore, increasing T increases competition more in the industry that depends more on telecommunication technologies (industry 1).

In an industry, firms might also use telecommunication technologies to increase product differentiation and reduce competition [i.e., $\varepsilon_i = \varepsilon_i(N_iT_i)$ and $\varepsilon_i' < 0$]. In such a case, the effect of increasing T on competitive pressure depends on the functional forms of $\varepsilon(.)$ and $F(.)$; therefore, *a priori* it can be ambiguous.

Increasing T may also increase the productivity of firms, λ. In this model, however, this would not affect LI given that we have assumed perfectly flexible prices. Relaxing this assumption can give another mechanism that can generate a positive relation between LI and T.

Finally, this model can be easily extended so that the firms live for more than one period and have operational fixed costs. In such a case, assuming free entry, firms' discounted value of revenue streams net of variable costs will be equal to the sum of entry and (the discounted value of) operational fixed costs. The decline of any of these fixed costs will intensify competition. Therefore, as long as increasing T reduces operational fixed costs and/or entry costs, increasing T will increase competition.

Appendix - Further Results

Alternative Measure for the Diffusion of Telecommunication Technologies

Our main measure of telecom diffusion is the number of fixed-lines and mobile telephone subscribers per capita (Telecom Subscribers). This variable, however, may not fully reflect the use and the quality of the telecommunication technologies, which can matter for the costs associated with information transmission.

For a robustness check of our results, we also use the revenue of the telecommunications industry per capita (hereafter, Telecom Revenue) as a telecom diffusion measure. This measure can better account for the use and quality. However, from the between-country-comparison perspective, it may fail to correctly reflect the amount of telecommunication services produced since it could be higher, for example, simply because prices are higher.[17]

We obtain the data for the revenue of the telecommunications industry from the GMID and ITU databases. Table 2.6 offers descriptive statistics for this and the remaining variables that we use for robustness checks, and Table 2.7 offers correlations between all country-level variables.

Column (1) in Table 2.12 offers the results where we use the (logarithm of) Telecom Revenue in 1997 as a measure of the diffusion of telecommunication technologies. In this column, we use our main measures for competition and dependence on telecommunication technologies. The estimated coefficient is negative and significant at the 1% level, which complements the result reported in column (1) of Table 2.2. Although the coefficient is somewhat smaller [-1.46 (0.24)], the predicted magnitude of the effect is higher, 0.030 (Hungary is at the 25th percentile, and Finland is at the 75th percentile in terms of the Telecom Revenue variable). We have also checked that all our remaining results are qualitatively the same for this measure.

As an additional robustness check we use the per capita number of internet subscribers as a measure of diffusion. The data were obtained from the GMID. Column (2) in Table 2.12 offers the results. The coefficient on the interaction term is again negative.

Alternative Measures for Dependence on Telecommunication Technologies

Our main measure of dependence on telecommunication technologies is the share of expenditures on telecommunications out of total expenditures on intermediate inputs in US industries. Our results would be wrong if this measure fails to correctly identify

[17] This problem may be alleviated with a purchasing power parity index for the telecommunications industry. We are not aware of any source of such data. Nevertheless, we have checked that our results are qualitatively not different if we adjust the revenue measure by the price of a 3-minute local mobile phone call.

the ranking of industries according to their dependence. For robustness checks we also use expenditures on telecommunications relative to output in US industries (the so-called "technical coefficients") and the coefficients of the inverse Leontief matrix of US industries as measures of telecom dependence.

We obtain the data for these measures from the input-output tables of the Bureau of Economic Analysis and average the measures over the 1997–2006 period. Table 2.8 offers rank correlations between all our measures of dependence on telecommunication technologies. Table 2.9 offers rank correlations between our main measures of telecom dependence and shares of expenditures on telecommunications in the industries in the EU countries in our sample.

Columns (3) and (4) in Table 2.12 offer the results where we use these dependence measures, while for competition and telecom diffusion we use our main measures. The estimated coefficients are again negative and significant which reaffirms our main result.

It can be also argued that European countries tend to be somewhat behind the United States in terms of the use of ICT. For a robustness check, we also employ the share of expenditures on telecommunications in 1994 in the United States.[18] Column (5) in Table 2.12 reports the results. The estimate of the coefficient is not different from our main result.

For a further robustness check, we also obtain industry-level data for the United Kingdom from the input-output tables from the OECD STAN database. Columns (6) in Table 2.12 offers the results where we use the UK data for measuring dependence on telecommunication technologies. The estimated coefficient is smaller in absolute value than our main result [-0.67 (0.39)]. However, it is not substantially smaller from the result for the measure identified from the OECD STAN database for the US, which is presented in column (2) of Table 2.3, [-1.65 (0.24)]. The former, in its turn, is quite close to the main result.

A reason behind such variation can be the higher noise in the UK data. For instance, the dependence measure identified from the data for the UK has lower rank correlations with the share of telecommunications expenditures in industries in the European Union countries compared to the measures identified from the data for the US (see Table 2.9).

We have further checked that all our (remaining) results are qualitatively the same for these alternative measures of dependence.

[18] We could use any date prior to 1997 and after 1993. It turns out that as we go towards 1993, our results become more pronounced and significant. This may partly stem from the technological lag between European Union countries and the United States.

Alternative Measures for Competition and Industry Share

We also calculate the price cost margin from firm-level data using the Amadeus database (PCMa) and employ it as a competition measure.

Tables 2.10 reports correlations between all our competition measures. Table 2.11 reports correlations between the remaining industry level variables.

Column (7) in Table 2.12 reports the results for the price cost margin, which is derived from the Amadeus database. The estimate of the coefficient on the interaction term has the expected sign and is significant. It is considerably smaller, though, than our main result [-0.55 (0.26)]. The predicted magnitude of the effect according to this estimate is also smaller, -0.004. However, relative to the mean of this measure, 0.09, the predicted magnitude is still comparably large, 5%.

Further, we have checked that our results hold when we take the number of firms from the Amadeus database, which, in contrast to the OECD STAN database, does not have full coverage.[19]

Finally, we have checked that our results are not qualitatively different if instead of the share in sales we use the share in value-added.

Alternative Estimators and Robustness to Outliers

The competition measure PCM varies from 0 to 1. We estimate the baseline specification (2.1) with Tobit and report the results in column (1) of Table 2.13. Further, in order to alleviate the influence of outliers, if any, we estimate the baseline specification using a quantile regression. We estimate it also on a sample that excludes the first and the last percentiles of the dependent variable, PCM. The results are reported in columns (2) and (3) of Table 2.13.

When appropriate, we have checked that all our results are qualitatively the same with these alternative estimators.

Alternative Sample Restrictions

Country-level – Is the UK different?

The UK might be expected to be different from the remaining countries, in terms of the use of telecommunication technologies and its development level. Column (4) in Table 2.13 excludes the UK from the sample. The result is the same as our main result.

Industry-level – Alternative measure for those that use telecommunications the least

[19] We have also used import penetration (imports over sales) as a competition measure. The data for that measure were obtained from the OECD STAN database. The estimated coefficient is positive, though not significant at the 10% level, and is not reported. The positive coefficient is consistent with the rest of our estimates. Meanwhile, the estimate is not significant perhaps because we have few data for that measure.

Our main measure for identifying the industries that use telecommunication technologies the least is the interaction between the variables industry share and telecom dependence. In a country, we take those industries that have a value lower than the median in the country.

As a robustness check in a country, we also take those industries that have below the median expenditures on telecommunications in 1995 in the country. The data for this measure were obtained from the input-output tables from the OECD STAN database. We use the dependence measure identified from that database in the estimation for this group of industries since the OECD STAN database has a slightly different aggregation.

Column (5) of Table 2.13 reports the results. The estimate of the coefficient is very close to the result which we have obtained using OECD STAN data for the dependence measure [column (2) of Table 2.3].

Alternative Additional Variables/Interaction Terms

In the main text for additional country-level variables that might proxy entry costs, we use various measures to identify the ranking of industries according to the effect of these variables. It may also be argued that the ranking of the industries according to their dependence on telecommunication technologies corresponds to the ranking of industries according to the effect these additional country-level variables have on them. In columns (1)-(6) of Table 2.14, we include the interactions of Telecom Dependence with the respective variable together with our main interaction term one-by-one. Our main result, again, stays basically unchanged.

Our measure for telecom diffusion, Telecom Subscribers, may proxy telecommunications industry regulation. The latter, meanwhile, may proxy for country-level market regulation and entry costs, which matter more for industries that have a higher dependence on telecommunication technologies. Although according to column (3) of Table 2.4 and column (2) of Table 2.14 most likely this is not driving our results, we continue exploring such a possibility. From the OECD Stat database, we obtain a measure of telecommunications industry regulation and include in our baseline specification its interaction with Telecom Dependence. Column (7) of Table 2.14 offers the results. Our main result is unaffected.[20]

It could also be that countries with bigger shadow economies have a lower reporting of output and lower competition due to the adherence to rather informal agreements.[21] Meanwhile, it could be that the industries that depend more on telecommunication technologies have a higher share in the shadow economy (e.g., services).

[20] We have also checked that the changes in economy-wide product market regulation and telecommunications industry regulation (i.e., differences between 2006 and 1997 values) do not drive our results.

[21] For example, in our sample PCM is 6% higher in countries where the shadow economy is more than the median compared to the remaining countries.

We take the measure of the size of the shadow economy and the data for it from Schneider (2002). This variable is in percentage of GNP and is averaged over the period 1999–2000. Column (1) of Table 2.15 includes the interaction of this variable with the measure of dependence on telecommunication technologies and reports the results. The estimate of the coefficient on our main interaction term is virtually not affected.

In the same vein, in the baseline specification (2.1), we have also included the interactions between GDP per capita and Telecom Dependence and CPI and Telecom Dependence [see columns (2) and (3) in Table 2.15]. The main result is, again, virtually unaffected.

Finally, we add to our baseline specification the initial intensity of competition in a industry-country pair. Columns (5) of Table 2.15 reports the results. The estimate of the coefficient on the interaction term stays negative which reaffirms our results.

Additional and Unreported Robustness Checks

We have performed further robustness checks. For example, we have checked that our results stay unaffected if we:

- use as a measure of telecom dependence the per capita number of broadband subscribers in 2000;
- include in the baseline specification the principal components of the matrix of all additional variables which explain more than 90% of the variation in the data. We have used principal components due to the high collinearity between variables;
- measure labor intensity with labor expenditures over output instead of the number of employees over output;
- add to the baseline specification the interactions of labor intensity and entry rate variables with the overall economic freedom index (in 1997) from the Heritage Foundation;
- measure financial development with private credit over GDP; and
- use other measures of human capital development from the Barro-Lee tables.

Summary Statistics and Correlations

Table 2.6: *Summary Statistics*

Variable	Obs.	Mean	SD	Min.	Max.
Country-level					
Corruption perception index in 1997 [CPI]	18	7.20	1.78	5.03	9.94
Real GDP per capita in 1997 [GDPC]	21	16140.24	8999.58	3517.05	35325.19
Shadow economy in 1999–2000 [Shadow Economy]	20	0.20	0.05	0.10	0.29
Telecom regulation in 1997 [Telecom Regulation]	18	3.86	1.32	1.05	5.63
Telecom revenue in 1997 [Telecom Revenue]	21	381.16	213.09	85.44	863.10
Internet subscribers in 1997 [Internet Subscribers]	21	0.02	0.02	0.00	0.07
Industry-level					
Coefficients of inverse Leontief matrix 1997–2006 [Telecom Dependence (Leontief)]	47	0.01	0.00	0.00	0.02
Telecom dependence in 1994 [Telecom Dependence (1994)]	47	0.01	0.01	0.00	0.06
Telecom dependence using UK data 1995–2005 [Telecom Dependence UK]	30	0.02	0.03	0.00	0.15
Telecommunications expenditures relative to output 1997–2006 [Telecom Dependence (Output)]	47	0.01	0.01	0.00	0.03
Industry-country-level					
Price cost margin from Amadeus data 1997–2006 [PCMa]	928	0.09	0.06	0.02	0.52
Price cost margin in 1997 [PCM (1997)]	840	0.19	0.14	0.00	0.90

Note: This table reports statistics for the key variables used in the paper. All variables and data sources are defined in detail in Table B in the Additional Data Appendix.

Table 2.7: *Correlations - Country-level Variables*

	Variable	1	2	3	4	5	6	7	8	9	10	11	12	13
1	B.Entry Cost													
2	Business Environment	0.10												
3	CPI	-0.52*	-0.06											
4	Financial Development	-0.29	0.02	0.43										
5	GDPC	-0.52*	0.17	0.76*	0.37									
6	Human Capital	-0.11	-0.07	0.27	-0.03	0.07								
7	Labor Regulation	-0.29	-0.25	0.17	0.16	0.04	-0.25							
8	Market Regulation	0.34	-0.04	-0.73*	-0.47*	-0.71*	-0.21	0.23						
9	Property Rights	-0.28	0.09	0.65*	0.26	0.72*	0.10	-0.31	-0.67*					
10	Shadow Economy	0.46*	-0.08	-0.67*	-0.36	-0.54*	-0.24	0.17	0.64*	-0.57*				
11	Telecom Regulation	0.20	-0.24	-0.36	-0.61*	-0.15	0.16	0.02	0.51*	-0.12	0.15			
12	Telecom Revenue	-0.49*	0.13	0.80*	0.47*	0.94*	0.08	-0.04	-0.78*	0.69*	-0.50*	-0.22		
13	Telecom Subscribers	-0.43	0.20	0.80*	0.45*	0.87*	0.04	0.20	-0.62*	0.56*	-0.39	-0.30	0.89*	
14	Internet Subscribers	-0.43	-0.01	0.81*	0.48*	0.72*	0.32	0.23	-0.52*	0.41	-0.31	-0.27	0.78*	0.84*

Note: This table shows the correlation coefficients between all country-level variables. See Table A in the Data Appendix and Table B in the Additional Data Appendix for complete definitions and sources of variables. * indicates 5% significance.

Table 2.8: *Rank Correlations - Telecom Dependence Measures*

Telecom Dependence []	EU	JP	The UK	–	(1994)	(Leontief)	(OECD)
JP	0.83						
The UK	0.78	0.80					
–	0.87	0.87	0.75				
(1994)	0.89	0.86	0.74	0.99			
(Leontief)	0.65	0.56	0.52	0.78	0.79		
(OECD)	0.85	0.81	0.80	0.88	0.89	0.80	
(Output)	0.83	0.84	0.69	0.97	0.97	0.86	0.87

Note: This table offers the pairwise Spearman's rank correlation coefficients between the measures of dependence on telecommunication technologies. See Table A in the Data Appendix and Table B in the Additional Data Appendix for the definitions and the data sources. All correlation coefficients are significant at the 1% level.

Table 2.9: *Rank Correlations - Telecom Dependence Measures and Shares of Expenditures on Telecommunications in EU Industries*

Telecom Dependence []	EU	JP	The UK	–	(OECD)
JP	0.83				
The UK	0.78	0.80			
–	0.87	0.87	0.75		
(OECD)	0.85	0.81	0.80	0.88	
Austria	0.83	0.72	0.71	0.68	0.78
Belgium	0.91	0.76	0.61	0.81	0.82
The Czech Republic	0.89	0.85	0.83	0.91	0.87
Denmark	0.85	0.81	0.77	0.81	0.80
Estonia	0.77	0.68	0.62	0.75	0.77
Finland	0.82	0.75	0.69	0.75	0.66
France	0.83	0.84	0.74	0.85	0.80
Germany	0.90	0.75	0.67	0.74	0.76
Greece	0.93	0.74	0.68	0.85	0.81
Hungary	0.82	0.87	0.75	0.90	0.81
Ireland	0.61	0.57	0.56	0.58	0.39
Italy	0.84	0.77	0.63	0.84	0.78
The Netherlands	0.83	0.75	0.78	0.83	0.82
Norway	0.71	0.57	0.50	0.63	0.58
Poland	0.83	0.77	0.73	0.78	0.85
Portugal	0.88	0.89	0.85	0.87	0.80
Slovakia	0.91	0.80	0.71	0.85	0.87
Slovenia	0.91	0.78	0.70	0.86	0.84
Spain	0.88	0.77	0.76	0.72	0.73
Sweden	0.87	0.64	0.68	0.72	0.80

Note: This table offers the pairwise Spearman's rank correlation coefficients between the measures of dependence on telecommunication technologies identified from the data for the US, the UK, and Japan and the share of telecommunications expenditures out of total expenditures on intermediate inputs in industries in EU countries. See Table A in the Data Appendix and Table B in the Additional Data Appendix for definitions and sources of variables. All correlation coefficients are significant at the 1% level.

Table 2.10: *Correlations - Competition Measures*

	HI	logN	MS	PCM	PCMa
logN	-0.66*				
MS	0.88*	-0.74*			
PCM	-0.00	0.16*	-0.06		
PCMa	0.16*	-0.19*	0.16*	0.49*	
PE	-0.24*	0.29*	-0.29*	0.27*	0.31*

Note: This table offers the pairwise correlation coefficients between competition measures. All measures are averaged over the period 1997–2006. See Table A in the Data Appendix and Table B in the Additional Data Appendix for complete definitions and sources of variables. * indicates the 5% level of significance.

Table 2.11: *Correlations - Industry-level Variables*

		1	2	3	4	5	6
1	Entry Rate						
2	Ext. Fin. Dependence	0.05					
3	Growth Potential EU	0.01	0.31*				
4	Growth Potential	0.20	0.43*	0.44*			
5	Labor Intensity	0.29	-0.03	-0.39	0.36		
6	R&D Intensity	0.42*	0.60*	0.22	0.44*	-0.10	
7	Telecom Dependence	0.35*	0.11	0.07	0.52*	0.31	0.14

Note: This table offers the pairwise correlation coefficients between industry-level variables, excluding the competition measures. See Table A in the Data Appendix and Table B in the Additional Data Appendix for complete definitions and sources of variables. * indicates the 5% level of significance.

Regression Results

Table 2.12: *Alternative Measures of Telecom Diffusion and Dependence*

	(1) Telecom Revenue	(2) Internet Subscribers	(3) (Output)	(4) (Leontief)	(5) (1994)	(6) UK	(7) PCMa
Telecom Dependence × Telecom Revenue	-1.46***						
	(0.24)						
Telecom Dependence × Internet Subscribers		-45.26***					
		(8.03)					
Telecom Dependence [ ] × Telecom Subscribers			-7.22***	-11.12***	-2.70***	-0.67**	
			(1.01)	(1.67)	(0.38)	(0.30)	
Telecom Dependence × Telecom Subscribers							-0.55**
							(0.26)
Industry Share	0.69***	0.65***	0.68***	0.70***	0.69***	0.79**	0.38***
	(0.27)	(0.27)	(0.26)	(0.27)	(0.27)	(0.32)	(0.10)
Observations	902	902	902	902	902	618	876
R2	0.71	0.71	0.72	0.72	0.72	0.74	0.49

Note: This table reports the results from the baseline specification (2.1) for various measures of telecom diffusion, dependence, and intensity of competition. In columns (1)-(6), the dependent variable is the competition measure PCM, which we calculate using OECD STAN data and average over the period 1997–2006. In column (1), the diffusion measure is the (logarithm of) Telecom Revenue in 1997. In column (2), the diffusion measure is the Internet Subscribers in 1997. In columns (3)-(6), we vary the dependence measure. In column (3), the dependence measure is the ratio of expenditures on telecommunications to output, Telecom Dependence (Output). In column (4), the dependence measure is US industries' coefficients of the inverse Leontief matrix, Telecom Dependence (Leontief). In column (5), the dependence measure is the share of expenditures on telecommunications out of expenditures on intermediate inputs in US industries in 1994, Telecom Dependence (1994). In column (6), the telecom dependence measure is identified from UK industries. In column (7), the dependent variable is the competition measure PCMa, which we calculate using Amadeus data and average over the period 1997–2006. We use our main measures of diffusion and dependence in column (7). See Table A in the Data Appendix and Table B in the Additional Data Appendix for complete definitions and sources of variables. All regressions include industry and country dummies and use the least squares estimation method. Robust standard errors are in parentheses. *** indicates significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table 2.13: *Alternative Estimators and Various Sample Restrictions*

	(1) Tobit	(2) Quantile	(3) OLS w/o 1 & 100%	(4) W/o UK	(5) Less Telecom User (Expenditure)
Telecom Dependence × Telecom Subscribers	-2.66*** (0.35)	-2.27*** (0.42)	-2.56*** (0.36)	-2.67*** (0.37)	
Telecom Dependence (OECD) × Telecom Subscribers					-1.16** (0.50)
Chow test (p-value)				0.80	0.03
Industry Share	0.69*** (0.25)	0.43* (0.25)	0.46** (0.22)	0.69** (0.28)	0.26 (0.54)
Observations	902	902	884	861	307
R2	-	0.50	0.68	0.72	0.70

Note: This table reports the results from the baseline specification for alternative estimators and various sample restrictions. The dependent variable is the competition measure PCM, averaged over the period 1997–2006. Column (1) reports the estimates from the Tobit regression with censoring at 0 and 1, and column (2) reports the estimates from a quantile regression. Columns (3)-(5) use the least squares estimation method. Column (3) reports the results for a sample that excludes the first and last percentiles of PCM. In column (4), the United Kingdom is excluded from the sample. Column (5) excludes the industries in a country that have higher-than-median expenditures on telecommunications in the country in 1995. For samples in columns (4)-(5), we perform Chow tests for the coefficients on the interaction terms. The p-values of corresponding t-statistics are reported in the row Chow test. See Table A in Data Appendix and Table B in the Additional Data Appendix for complete definitions and sources of variables. Pseudo R2 is reported for the quantile regression. All regressions include industry and country dummies. Robust standard errors are in parentheses. ***indicates significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table 2.14: *Specification Check - Additional Variables*

	(1) B.Entry Cost	(2) Market Regulation	(3) Financial Development	(4) Labor Regulation	(5) Property Rights	(6) Human Capital	(7) Telecom Regulation
Telecom Dependence × Telecom Subscribers	-2.49*** (0.40)	-3.17*** (0.71)	-2.55*** (0.41)	-2.68*** (0.37)	-3.50*** (0.47)	-2.69*** (0.36)	-3.34*** (0.45)
Telecom Dependence × B.Entry Cost	1.07 (1.07)						
Telecom Dependence × Market Regulation		0.11 (0.47)					
Telecom Dependence × Financial Development			-0.43 (0.76)				
Telecom Dependence × Labor Regulation				-0.19 (1.34)			
Telecom Dependence × Property Rights					4.36*** (1.47)		
Telecom Dependence × Human Capital						-2.01 (1.28)	
Telecom Dependence × Telecom Regulation							-0.05 (0.13)
Industry Share	0.72*** (0.26)	0.80*** (0.28)	0.69*** (0.27)	0.72*** (0.26)	0.67** (0.27)	0.69*** (0.26)	0.79*** (0.27)
Observations	857	769	902	857	902	902	769
R2	0.71	0.70	0.72	0.71	0.72	0.72	0.70

Note: This table reports the results from specifications that augment the baseline with additional interaction terms. The dependent variable is the competition measure PCM averaged over the period 1997–2006. See Table A in Data Appendix and Table B in Additional Data Appendix for complete definitions and sources of variables. All regressions include industry and country dummies and use the least squares estimation method. Robust standard errors are in parentheses. *** indicates significance at the 1% level, ** at the 5% level, and * at the 10% level.

Table 2.15: *Specification Check - Additional Variables*

	(1) Shadow Economy	(2) GDPC	(3) CPI	(4) PCM (1997)
Telecom Dependence × Telecom Subscribers	-2.64*** (0.43)	-2.56*** (0.77)	-3.52*** (0.73)	-0.70*** (0.27)
Telecom Dependence × Shadow Economy	0.86 (3.73)			
Telecom Dependence × GDPC		-0.06 (0.44)		
Telecom Dependence × CPI			0.06 (0.17)	
PCM (1997)				0.73*** (0.03)
Industry Share	0.72*** (0.26)	0.69** (0.27)	0.79*** (0.27)	0.02 (0.08)
Observations	857	902	769	840
R2	0.71	0.72	0.70	0.93

Note: This table reports the results from specifications that augment the baseline with additional variables/interaction terms. The dependent variable is the competition measure PCM averaged over the period 1997–2006. See Table A in the Data Appendix and Table B in the Additional Data Appendix for complete definitions and sources of variables. All regressions include industry and country dummies and use the least squares estimation method. Robust standard errors are in parentheses. *** indicates significance at the 1% level, ** at the 5% level, and * at the 10% level.

Additional Data Appendix

Table B: *Definitions and Sources of Additional Variables*

Variable Name	Definition and Source
Country-level Variables	
CPI	Corruption perception index. The data are for 1997. Source: Transparency International.
GDPC	GDP per capita (in 2000 US$). The data are for 1997. Source: WDI.
Telecom Regulation	Telecommunications industry regulation indicator in 1997. This indicator takes into account public control, entry and market structure. Source: OECD Stat.
Telecom Revenue	The revenue of the telecommunications industry per capita (in 2000 US$). The data are for 1997. Source: ITU and GMID.
Internet Subscribers	The per capita number of total internet subscriptions with fixed (wired) access. The data are for 1997. Source: ITU and GMID.
Shadow Economy	The size of the informal economy as the share of GNP, averaged over the period 1999-2000. Source: Schneider (2002).
Industry-level Variables	
Telecom Dependence UK	The share of (real) expenditures on telecommunications out of expenditures on intermediate inputs in UK industries, averaged over the years 1995, 2000, and 2005. Source: Authors' calculations using data from OECD STAN, I-O tables.
Telecom Dependence (1994)	The share of (real) expenditures on telecommunications out of expenditures on intermediate inputs in US industries in 1994. Source: Authors' calculations using data from BEA, I-O tables.
Telecom Dependence (Leaontief)	The coefficients of the inverse Leontief matrix of US industries, averaged over 1997–2006. Source: Authors' calculations using data from BEA, I-O tables.
Telecom Dependence (Output)	The ratio of (real) expenditures on telecommunications to output in US industries, averaged over 1997–2006. Source: Authors' calculations using data from BEA, I-O tables.
Industry-country-level Variables	
PCMa	Price cost margin is defined as the weighted average of firm-level price cost margins computed as operational profit over operational revenue within an industry, averaged over 1997–2006. Source: Authors' calculations using data from Amadeus.
PCM (1997)	PCM in 1997. Source: Authors' calculations using data from OECD STAN.
Least Telecom Users (Expenditure)	Dummy variable that takes value 1 for a industry-country pair if expenditures on telecommunications are below the median in 1995 in the country, and zero otherwise. Source: Authors' calculations using data from OECD STAN and BEA.

Appendix - Data Cleaning

The Amadeus database is a product of Bureau van Dijk. It consists of full and standardized information from balance sheets and profit/loss account items, identification information, and the industry codes of European firms.

Amadeus has a specific feature regarding the exclusion of firms from the database. If a firm exits or stops reporting its financial data, Amadeus keeps this firm four years and then excludes it from the database. For example, in the 2010 edition of Amadeus, the data for 2006 do not include firms that exited in 2006 or before. For our analysis, we need to have as full a dataset as possible in order to obtain competition measures that better approximate the real intensity of competition. Therefore, we combine and use several Amadeus editions: March 2011, May 2010, and June 2007 downloaded from WRDS and August 2003 and October 2001 DVD updates from Bureau van Dijk.

From the Amadeus database, we take operational revenues (for computing the Herfindahl index and the market share of the four largest firms), operational profits (for computing the PCM), and the industry codes of the firms. We transform all industry codes into ISIC rev. 3.1. We perform basic data cleaning in order to reduce potential selection bias and measurement errors by:

- dropping the firms that do not report operational revenue or total assets and firms that report their data in consolidated statements;
- imputing the missing values of key variables using linear interpolation across years. This helps to restore possibly erroneously missing values;
- dropping the industries which have less than four firms in a given year;
- defining severe outliers as the first and the last percentiles of relative yearly changes in operational revenue and total assets for each country and the 2-digit industry code. If an outlier is at the beginning or at the end of the time period for a firm, then only the first or last observation is dropped. If an outlier is in the middle of the time period, the whole firm is dropped; and
- excluding observations with PCM below 0 and above 1 while computing the PCM.

Chapter 3

Specific and General Human Capital in an Endogenous Growth Model

(Joint work with Evangelia Vourvachaki and Sergey Slobodyan)

Abstract

In this paper, we define specific (general) human capital in terms of the occupations whose use is spread in a limited (wide) set of industries. We analyze the growth impact of an economy's composition of specific and general human capital, in a model where education and R&D are costly and complementary activities. The model suggests that there can be long-run welfare costs involved in a declining share of specific human capital as observed in the Czech Republic. We also discuss optimal educational policies in the presence of market frictions.

JEL Codes: O52; O40; O49; I20
Keywords: Human capital types; Education policy; Endogenous growth

This work is dedicated to the memory of Viatcheslav Vinogradov, the author of the original research idea, the project's inspiration, and its first leader. An earlier version of this work is available online as Vourvachaki, Jerbashian, and Slobodyan (2013). This work was presented at the 2nd Armenian Economic Association meeting in Yerevan (2012). The support of GA ČR grant IAA 700850902 is gratefully acknowledged. All errors remaining in this text are the responsibility of the author.

3.1 Introduction

Education systems across developed countries are highly diverse with respect to their financing (private vs. public), structure and philosophy (e.g., see OECD, 2010). Because of this, even though there is no high cross-country variation in terms of the average level of skills (e.g., in terms of average years of schooling, see the Barro-Lee data), there is important variation in terms of the types of skills developed via education across countries and time. A number of studies examine the role of the latter for economic outcomes at the individual or aggregate level. One stream of literature differentiates skills according to their "vocational intensity," where a vocation is associated with "practical and technical" skills (e.g., see Krueger and Kumar, 2004a,b; Hanushek, Wössmann, and Zhang, 2011). Another stream of literature differentiates skills according to the "routine intensity" of the tasks performed as part of an occupation, where high routine intensity is associated with "codifiable" tasks (e.g., see Autor and Dorn, 2009; Acemoglu and Autor, 2011).

We propose an alternative way to horizontally differentiate across skill types in order to analyze the impact of human capital composition on aggregate economic performance. Similarly to existing literature, we exploit the cross-occupational differences. Our point of departure is that our definition derives from cross-industry heterogeneity in the production function: We differentiate human capital skills according to their "industry specificity." This builds a sufficiently general conceptual framework to analyze the impact of shocks, aggregate or industry-specific, skill-biased technology or not.

In particular, we define two distinct types of human capital: "general" and "specific." As general human capital, we define a set of skills that enable individuals to perform generic tasks that are required for production in a wide range of industries (e.g., services skills of managers, manual skills of cleaners). In contrast, specific human capital is defined as a set of skills that enable one to perform highly specialized tasks in few industries (e.g., the cognitive skills of doctors, manual skills of craft workers).[2]

Our classification is used to summarize the facts regarding the employment and education levels of the two human capital types for the Czech economy. This results in a rather uniform level of skills across the specific and general human capital, which agrees with our horizontal differentiation of skills. We find that in 2007, approximately 36 percent of the total labor input is comprised of specific human capital. Moreover, the evidence suggests that this share has been steadily falling since the mid-1990s.

To illustrate how this horizontal differentiation of human capital can matter for long-run growth and welfare, we build up an endogenous growth model, where edu-

[2] Our definitions of specific and general skills are conceptually similar with Becker's definitions in Becker (1962).

cation and R&D are costly activities. In the model, both general and specific human capital are used in final goods production, while only specific human capital can serve as input into the educational sector and R&D. This structure highlights that specific, intensive training on the details of production is essential for the ability to innovate or train new human capital. We also explicitly take into account the acclaimed complementarity between basic and/or applied R&D and education processes and positive externalities in R&D (e.g., see Griliches, 1992; Nadiri, 1993; Jones and Williams, 1998).[3] In such a context, there is underinvestment in R&D at the aggregate level because economic agents do not fully internalize the benefits of their R&D investments. The more the economic agents internalize the benefits of their investments, the more they accumulate specific human capital. Because the latter is the engine of growth, the economy enjoys higher growth.

Our theoretical framework can be used to gain an insight into what can drive the decline in the share of specific human capital that is observed in the Czech economy. We note that to the extent a more centralized education system is more suitable to account for any economy-wide human capital externalities, then our model suggests that the Czech Republic would have been endowed with a high level of specific human capital.[4] In turn, the gradual decentralization of the Czech educational system and interest in individual-level wage returns would imply a declining share of specific human capital, which is consistent with Czech data. In this respect, our model suggests that in an otherwise frictionless and stable economic environment, this trend could involve significant long-run welfare costs.

This framework offers other potentially plausible explanations for the falling share of specific human capital as observed in the Czech Republic. For example, it suggests that such a pattern can hold if the efficiency of the education process of general human capital increases relative to the efficiency of the education process of specific human capital. This explanation can be reasonable to the extent that technical change implied by the introduction of IT could have increased the efficiency in the education process in the field of Computing, relative to other fields. Meanwhile, more than 90% of the graduates in this field have general human capital according to our classification and data for the Czech Republic. It further suggests that such a pattern can hold in case when the centralized economy involved frictions and over accumulated specific human capital (e.g., due to political objectives). Clearly, if these were complete explanations,

[3] Acemoglu and Angrist (2000) and Moretti (2003) identify significant and positive human capital externalities. The presence of such externalities implies that in a decentralized equilibrium, returns on human capital are lower than is socially optimal. In our case, it also implies that there is less R&D than is socially optimal which is in line with, for example, Jones and Williams (1998).

[4] The returns from sharing experience/knowledge might be easier to appropriate in a more centralized environment since it can be easy to track the use of shared knowledge in such an environment.

the declining share would not necessarily involve welfare costs.[5]

The policy implications derived from the model contribute to the debate concerning the role of public education and R&D and their finance in light of the recent crisis and subsequent budgetary cuts. For example, the United States and the United Kingdom were the first countries to move towards limiting the funds for public education, while in the United Kingdom this has been more the case in individual fields such as humanities. The Czech Republic, among other European countries, is also considering taking action in similar directions. Our results highlight that to the extent market distortions cannot be excluded, long-run welfare can be promoted by introducing subsidies to the returns on human capital, which would encourage its accumulation.

With regards to the model, we relate to the endogenous growth literature that focuses on input accumulation, like Romer (1990) and Lucas (1988). Closer to our framework is the model presented in Eicher (1996), where educational investment is costly, and technology advances as its by-product. Our main innovation is that we allow households to internalize partially the benefits from their inventions.

Finally, our work relates broadly to studies that examine the intra- and inter-temporal trade-offs between different types of human capital in environments with high uncertainty, the introduction of new technologies, or trade. Such mechanisms are analyzed in Autor and Dorn (2009), Krueger and Kumar (2004a,b), Gould, Moav, and Weinberg (2001), Hummels, Jørgensen, Munch, and Xiang (2011) among others. Sarychev (1999) offers a theoretical model specific to the transition experience from centrally planned economies to market based ones. Generalizing the economic environment of our model in the spirit of the aforementioned studies would necessarily benefit the relative value of general human capital in our framework. Thereby, our baseline results regarding the benefits from increasing the intensity of specific human capital will not generalize in a straightforward way. Nevertheless, our present framework is sufficiently parsimonious to highlight the benefits of specific human capital in the long-run and study the impact of the composition of human capital types on welfare.

The paper is organized as follows. Section 2 discusses the composition of specific and general human capital in the Czech Republic. Section 3 presents the model and its results. Section 4 concludes.

[5] The observed trend can be also the net output of a number of different factors apart from those that we highlight in our stylized model, like structural change or regulatory barriers.

3.2 General and Specific Human Capital: The Case of the Czech Republic

We treat every occupation as defining a particular set of skills that enable the performance of specific tasks that are necessary as a part of the production process. In this respect, occupations tightly define the labor services input in the production of each industry. To the extent that industries differ in their technological needs in terms of the types of labor services, their demand for occupations would also be different. If input/output markets are frictionless, then the observed demand for an occupation by different industries can be used to figure out the degree of an occupation's "industry specificity." We classify an occupation as "specific human capital" if it is used by a limited set of industries, i.e., its employment share exhibits a high degree of concentration across industries. Accordingly, we classify an occupation as "general human capital" if it is used in the production of a wide variety of products, i.e., its employment share has a high degree of dispersion.

Employing our definition of specific human capital, we systematically summarize how specific skills are produced and used in the Czech economy. The details of the sources and properties of the data, and the methodology we used to group data according to human capital skill types, are provided in Appendices D.1 and D.2. The summary tables with the detailed list of occupations and education fields that are associated with specific human capital, as well as all figures, are offered at the end of the paper.

The results tend to be intuitive. As an illustration, health professionals are classified as specific human capital since they are employed almost exclusively (80%) in the health industry. The health industry itself is highly intensive in health professionals (40% of total labor input). The training for such professionals comes almost exclusively from the health field.[6] On the contrary, another highly skilled group, corporate managers, is classified as general human capital since they are almost evenly distributed across all industries. They are used rather non-intensively and can graduate from a wide set of fields: from business and administration to engineering. We also observe seemingly counterintuitive cases of highly skilled groups (lawyers), which are employed by a wide variety of industries despite being trained (almost) exclusively in the educational field of law and, thus, classified as general human capital.

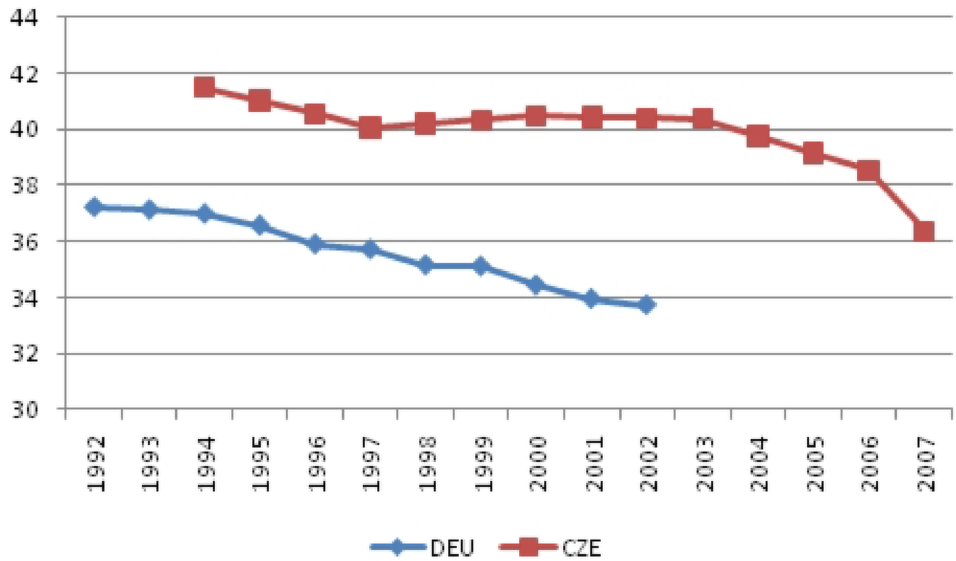
Importantly, the average distribution of skill-levels across the two types of human capital is such that no human capital type is singled out as exclusively high- or low-skilled. As an illustration, 92% of workers with specific human capital have completed

[6] The relationship between education and the training of health care professionals could be overstated since they are typically obligated by law to have training in medicine.

the basic education and have at least ISCED-97 education level 3, while 14% are graduates of ISCED-97 levels 5-6 , as opposed to 95% and 16% respectively for the workers with general human capital.

The overall employment (use) share of specific human capital is 36.4% for 2007.[7] Figure 3.1 illustrates how the employment share of specific human capital has evolved over the period 1994-2007 in the Czech Republic.[8]

Figure 3.1: *The Employment Share of Specific Human Capital*



Note: This figure offers the employment share of specific human capital in the Czech Republic for the period 1994-2007 and for Germany for the period 1992-2002.

There is a clear downward trend with the share falling by 5 percentage points over the course of the entire period. The downward trend in the employment of specific human capital is not specific to the Czech Republic since Germany matches it over the course of 1992-2002.[9]

Concerning the production of specific skills, we highlight the education fields whose majority of graduates (more than 50%) end up in specific human capital related occupations according to our employment data. In 2007, 34.5% of total graduates in the Czech Republic graduated from fields that intensively produce specific human capital. The corresponding share in 2007 for Germany was 35% and 34% for the Euro area. In

[7] This excludes military personnel, ISCO-88 0.

[8] The information for the period 1994-2002 is taken from Jeong, Kejak, and Vinogradov (2008). For this period, the calculation of the specific human capital employment share excludes ISCO-88 62 as the relevant data are not reported in the original source.

[9] The downward trend is further confirmed by the European average employment share data by occupation that we obtain from Goos, Manning, and Salomons (2010). The average employment share of specific human capital in Europe was 36.3% in 1993 and decreased to 31.3% by 2006. This evidence excludes ISCO-88 11, 6, 33, 23, 92, as these occupations are not reported. Excluding the same ISCO-88 codes in our data, we find that the Czech Republic moved from an employment share of 34.6% in 1994 to 31.8% in 2007.

2000, the share for the Czech Republic is also close to its German counterpart (33.1% and 30.6% respectively). We do not have sufficiently long data to comment on the existence of any systematic time patterns. Moreover, there are further limitations in this respect, as educational data are bound to lag behind labor market developments due to demographics, difficulty to change institutions and culture, uncertainty, etc.

Overall, the data presented here show that the Czech Republic has changed its composition of human capital types in a way that closely matches its neighbors. This outcome may strike one as surprising as the Czech Republic, among other former transition and Central European countries, is often presented as a "vocational" economy. For example, in their recent review Hanushek et al. (2011) show that the Czech Republic, Hungary and Poland together with Germany and Switzerland feature as top apprenticeship countries in Europe with 72% of the male population completing "vocational education," and with the rest completing "general education." Notably though, they define the latter as "tertiary type-A programs [...] largely theory-based [...] designed to provide sufficient qualifications for entry to advanced research programs and professions with high skill requirements"(p. 9).[10] In this respect, their definition is more tied to the level of skills than to the type of skills and the degree to which they are used for the production of a wide range of products, which is our own primary focus. This highlights the importance of the original choice of the definition for specific human capital.

3.3 The Model

The final goods (Y) producers use physical capital (K), specific human capital (H_s) and general human capital (H_g), in order to produce homogenous goods.

The economy is populated by a continuum of infinitely lived and identical households of mass one. The representative household owns all types of physical and human capital and derives utility from the consumption (C) of final goods. The household finances its consumption expenditures with the labor income and interest earned on capital. The household rents its two types of human capital and physical capital at the prevailing market prices (w_s, w_g, and r, respectively).

Further, the household can accumulate either type of its human capital through education. Having an intensive training on the details of production, the specific human capital is the necessary input in the education process. Each human capital has a different accumulation process in the education sector (i.e., different schooling function).[11]

[10] See footnote 7 in Hanushek et al. (2011).

[11] Human capital accumulation processes in our model can constitute any type of training.

Human capital employed in the schooling of specific human capital also engages in generation of new technology. This process captures the R&D in education-related institutions. The technology generated through this process improves the quality of the physical capital.

Given that the household owns physical capital and the innovations are embodied in it, the household internalizes this R&D process and its effect on physical capital. In the spirit of Romer (1990) and Lucas (1988), the household has decreasing returns from that process; however, the externalities that stem from others' involvement in R&D make the returns constant at the aggregate level.[12] These externalities stem from knowledge sharing between researchers, where the level of knowledge of researchers is proportional to the level of their human capital.[13]

Final Goods Sector

The production function of final goods is given by

$$Y = \lambda_Y H_g^{\gamma_1} \left[\left(u_Y^s H_s \right)^{\gamma_2} K^{1-\gamma_2} \right]^{1-\gamma_1}, \qquad (3.1)$$
$$1 > \gamma_1 > 0, 1 > \gamma_2 > 0, \lambda_Y > 0,$$

where λ_Y is an exogenous productivity level, and u_Y^s is the share of specific human capital employed in the production of final goods.

Setting the final goods as the numeraire, the optimization problem of a representative producer is

$$\max_{H_g, u_Y^s H_s, K} \left\{ Y - w_g H_g - w_s u_Y^s H_s - rK \right\}, \qquad (3.2)$$
$$s.t. \;\; (3.1).$$

The resulting optimal rules are

$$w_g H_g = \gamma_1 Y, \qquad (3.3)$$
$$w_s u_Y^s H_s = (1-\gamma_1)\gamma_2 Y, \qquad (3.4)$$
$$rK = (1-\gamma_1)(1-\gamma_2) Y. \qquad (3.5)$$

The first expression is the final goods producer's demand for general human capital. The second and third are the demands for specific human capital and physical capital, respectively.

[12] Constant returns are required in order to have a balanced growth path.

[13] We abstract from any issues of obsolescence and any further labor market frictions in order to highlight the impact of friction in R&D on human capital allocations.

Education Sector

Specific and general types of human capital have different accumulation processes (schooling functions), where the only input is the specific human capital.[14] The accumulation processes are

$$\dot{H}_s = \lambda_s u_s^s H_s, \tag{3.6}$$

$$\dot{H}_g = \lambda_g u_g^s H_s, \tag{3.7}$$

respectively, where λ_s, $\lambda_g > 0$ are exogenous productivity levels, and u_s^s and u_g^s are the shares of specific human capital employed in the respective accumulation processes.

The human capital employed in the accumulation of specific human capital also produces new technology Λ according to the following rule

$$\dot{\Lambda} = \delta \left(u_s^s H_s \right)^{\gamma_3}, \tag{3.8}$$

where $1 \geq \gamma_3 \geq 0$, and δ is a productivity level that is exogenous from an individual perspective. The technology thus generated improves the quality of physical capital:

$$K = \Lambda k, \tag{3.9}$$

where k is normalized to 1.

At the aggregate level, there are constant returns in the R&D process, and δ is given by

$$\delta = \lambda_\Lambda \left(u_s^s H_s \right)^{1-\gamma_3}, \tag{3.10}$$

where $\lambda_\Lambda > 0$ is an exogenous productivity level. Therefore, $1 - \gamma_3$ equals the degree of externalities that stem from others' involvement in R&D. In the limiting case when $\gamma_3 = 1$, there are no such externalities, whereas when $\gamma_3 = 0$, the R&D process *per se* is an externality.

Households

The representative household has a standard CIES utility function with an intertemporal substitution parameter $\frac{1}{\theta}$ and discounts the future streams of utility with rate ρ $(\theta, \rho > 0)$. The lifetime utility of the household is

$$U = \int_0^{+\infty} \frac{C_t^{1-\theta} - 1}{1-\theta} \exp\left(-\rho t\right) dt. \tag{3.11}$$

[14] The inclusion of physical capital in human capital accumulation processes does not change our results though it makes the algebra more cumbersome.

The household's decisions follow its preferences and satisfy its budget constraint

$$0 = rK + w_s u_Y^s \left(1+\tau_Y^s\right) H_s + w_g \left(1+\tau_Y^g\right) H_g - C - T, \tag{3.12}$$
$$1 \geq \tau_Y^s \geq -1, 1 \geq \tau_Y^g \geq -1,$$

where the triple $\{\tau_Y^s, \tau_Y^g, T\}$ represents government policy consisting of proportional taxes (or subsidies) on earnings from specific and general human capital employed in the production of final goods and a lump-sum tax T. The tax T, which is needed to balance the government budget, in equilibrium is given by

$$T = w_s u_Y^s \tau_Y^s H_s + w_g \tau_Y^g H_g. \tag{3.13}$$

The sum of shares of specific capital in the education and final goods sectors is

$$1 \geq u_Y^s + u_s^s + u_g^s. \tag{3.14}$$

The household's optimal problem, therefore, is

$$\max_{u_Y^s, u_g^s, C} U = \int_0^{+\infty} \frac{C_t^{1-\theta} - 1}{1-\theta} \exp\left(-\rho t\right) dt$$
$$s.t.$$
$$\left(3.12\right), \left(3.6\right), \left(3.7\right), \left(3.8\right), \left(3.9\right), \left(3.14\right),$$
$$H_s\left(0\right), H_g\left(0\right), \Lambda\left(0\right) > 0 - given.$$

Assigning shadow values $\{q_i\}$ to constraints (3.12), (3.6), (3.7), and (3.8), the decision rules that follow from the household's optimization are

$$C^{-\theta} = q_1, \tag{3.15}$$
$$q_1 w_s \left(1+\tau_Y^s\right) H_s = q_2 \frac{\dot{H}_s}{u_s^s} + q_4 \gamma_3 \frac{\dot{\Lambda}}{u_s^s}, \tag{3.16}$$
$$q_3 \frac{\dot{H}_g}{u_g^s} = q_2 \frac{\dot{H}_s}{u_s^s} + q_4 \gamma_3 \frac{\dot{\Lambda}}{u_s^s}, \tag{3.17}$$
$$\dot{q}_2 = q_2 \rho - \left[q_1 w_s u_Y^s \left(1+\tau_Y^s\right) + q_2 \frac{\dot{H}_s}{H_s} + q_3 \frac{\dot{H}_g}{H_s} + q_4 \gamma_3 \frac{\dot{\Lambda}}{H_s} \right], \tag{3.18}$$
$$\dot{q}_3 = q_3 \rho - q_1 w_g \left(1+\tau_Y^g\right), \tag{3.19}$$
$$\dot{q}_4 = q_4 \rho - q_1 r k. \tag{3.20}$$

The first optimal decision is for the consumption path. The next two are the allocations of specific human capital in the final goods and education sectors, where the second term on the right-hand side is the value stemming from R&D (voluntarily) performed by the specific human capital.[15] The remaining decision rules describe the returns on the accumulation of specific and general human capitals and technology.[16]

Using letter g for the growth rates of variables and expressions (3.3), (3.4), (3.5), (3.16), and (3.17), the returns on accumulation of all types of asset holdings can be rewritten as

$$-g_{q_2} = \lambda_s + \lambda_\Lambda \gamma_3 \frac{q_4}{q_2} - \rho, \tag{3.21}$$

$$-g_{q_3} = \lambda_g \frac{1+\tau_Y^g}{1+\tau_Y^s} \frac{\gamma_1}{(1-\gamma_1)\gamma_2} \frac{H_s}{H_g} u_Y^s - \rho, \tag{3.22}$$

$$-g_{q_4} = \frac{1-\gamma_2}{\gamma_2} \frac{1}{1+\tau_Y^s} \frac{H_s}{\Lambda} u_Y^s \left(\lambda_s \frac{q_2}{q_4} + \gamma_3 \lambda_\Lambda\right) - \rho. \tag{3.23}$$

The ratio $\frac{q_4}{q_2}$ shows the value from relaxing the constraint for $\dot{\Lambda}$, (3.8), compared to the value from relaxing the constraint for $\dot{H}_s$, (3.6). According to (3.21) and (3.23), the return on the accumulation of specific human capital $-g_{q_2}$ increases with that ratio, whereas the return on the accumulation of technology $-g_{q_4}$ declines with it.

3.4 Features of the Dynamic Equilibrium

The results regarding the balanced growth path behavior of the economy are the following.

Proposition 1. *The balanced growth path growth rates and allocations of the economy can be derived from the root(s) of the following quadratic polynomial of* $\frac{q_4}{q_2}$.

$$\begin{aligned} P\left(\frac{q_4}{q_2}\right) = & \left[\theta + \frac{1+\tau_Y^g}{1+\tau_Y^s} \frac{\gamma_1}{(1-\gamma_1)\gamma_2} + \frac{1-\gamma_2}{\gamma_2} \frac{1}{1+\tau_Y^s} \gamma_3\right] \frac{1}{\theta} \lambda_\Lambda \gamma_3 \left(\frac{q_4}{q_2}\right)^2 \\ & + \left\{\left[1 + \frac{1}{\theta} \frac{1+\tau_Y^g}{1+\tau_Y^s} \frac{\gamma_1}{(1-\gamma_1)\gamma_2}\right](\lambda_s - \rho) + \rho \right. \\ & \left. + \frac{\lambda_s (2-\theta) - \rho}{\theta} \frac{1-\gamma_2}{\gamma_2} \gamma_3 \frac{1}{1+\tau_Y^s}\right\} \frac{q_4}{q_2} \\ & - \frac{1-\gamma_2}{\gamma_2} \frac{1}{1+\tau_Y^s} \frac{\lambda_s}{\lambda_\Lambda} \left[\lambda_s - \frac{1}{\theta}(\lambda_s - \rho)\right]. \end{aligned} \tag{3.24}$$

Proof. See Appendix T.1. □

[15] When $\gamma_3 = 0$, the second term in the right-hand side of expressions (3.16) and (3.17) is zero since R&D is a pure externality for the household.

[16] Given that the pair (τ_Y^s, τ_Y^g) affects the household's trade-off between training and working, it is referred to as *education policy* in this model.

Since the quadratic coefficient is positive, a sufficient condition for two real roots is a negative free term. The free term is negative when

$$\theta \geq 1. \tag{3.25}$$

This condition implies that the household needs to have a relatively low elasticity of inter-temporal substitution. It is a common condition that ensures balanced growth in multi-sector growth models. In our framework, it implies also that there is only one positive root. Hereafter, it is assumed that (3.25) holds.

Proposition 2. *In the decentralized equilibrium on the balanced growth path, all quantities grow at the same rate*

$$g = \frac{1}{\theta}\left(\lambda_s + \lambda_\Lambda \gamma_3 \frac{q_4}{q_2} - \rho\right), \tag{3.26}$$

where $\frac{q_4}{q_2}$ *is the positive root of the polynomial* $P\left(\frac{q_4}{q_2}\right)$*. Moreover, all relative prices are constant, and the growth rates of shadow values* q_1, q_2, q_3, *and* q_4 *are equal.*

Proof. See Appendix T.1 which also offers the system of equations that can be solved for the relative allocations. □

Therefore, the condition that ensures a positive growth rate of consumption on the balanced growth path is

$$\lambda_s + \lambda_\Lambda \gamma_3 \frac{q_4}{q_2} > \rho. \tag{3.27}$$

Together with (3.25) this condition is necessary in order to have bounded lifetime utility. Hereafter, it is assumed that (3.27) holds for any value of γ_3, which is equivalent to assuming that $\lambda_s > \rho$.

In order to highlight the properties of the decentralized equilibrium, Table 3.1 offers the (main) comparative statics. Some of the derivatives in this table are obtained using numerical methods since the analytical derivations become cumbersome due to high non-linearity of equations (for further details see Appendix T.1).

The non-linearity arises because the return on the accumulation of specific human capital $-g_{q_2}$ increases with $\frac{q_4}{q_2}$, while the return on accumulation of technology $-g_{q_4}$ declines with it, but on the balanced growth path they need to be equal. When R&D is pure externality (i.e., $\gamma_3 = 0$), $-g_{q_2}$ does not depend on $\frac{q_4}{q_2}$, and the comparative statics are easily computed. Appendix E.1 presents derivations for this case.[17]

[17] The return on the accumulation of specific human capital $-g_{q_2}$ also does not depend on the ratio $\frac{q_4}{q_2}$ when the allocation of specific human capital to R&D activity is a (separate) choice variable. In this case, the comparative statics can be derived analytically (see Appendix E.2).

Table 3.1: *Comparative Statics*

		q_4/q_2	q_3/q_2	H_s/H_g	H_s/Λ	g	u_s^s	u_g^s	u_Y^s	u_s^s/u_g^s
ρ	$[0.001, 0.09]$	$+$	$+$	$-$	0	$-$	$-$	$\pm$	$+$	$-$
θ	$[1, 10]$	$+$	$+$	$-$	0	$-$	$-$	$\pm$	$+$	$-$
γ_1	$[0.01, 0.99]$	$-$	$-$	$-$	0	$-$	$-$	$+$	$-$	$-$
γ_2	$[0.01, 0.99]$	$-$	$-$	$\pm$	0	$-$	$-$	$\pm$	$+$	$\pm$
γ_3	$[0.01, 0.99]$	$\pm$	$+$	$+$	0	$+$	$+$	$\pm$	$-$	$+$
λ_s	$[0.1, 10]$	$\pm$	$+$	$+$	$+$	$+$	$+$	$\pm$	$-$	$+$
λ_g		0	$-$	$-$	0	0	0	0	0	0
$\lambda_s, \lambda_s \equiv \lambda_g$	$[0.1, 10]$	$\pm$	$-$	$+$	$+$	$+$	$+$	$\pm$	$-$	$+$
λ_Λ		$-$	0	0	$-$	0	0	0	0	0
τ_Y^s	$[-0.99, 0.99]$	$-$	$-$	$+$	0	$-$	$-$	$-$	$+$	$+$
$\tau_Y^s, \tau_Y^g \equiv \tau_Y^s$	$[-0.99, 0.99]$	$-$	$-$	$-$	0	$-$	$-$	$\pm$	$+$	$-$

Note: The sign $+$ means a positive relationship, $-$ negative, 0 no relationship, and $\pm$ means that the relationship depends on model parameters. Some of these comparative statics were derived with a numerical exercise (see for details Appendix T.1). The intervals for parameter values used in the exercise are offered in the table, where the grids are equally spaced and each has 5 points.

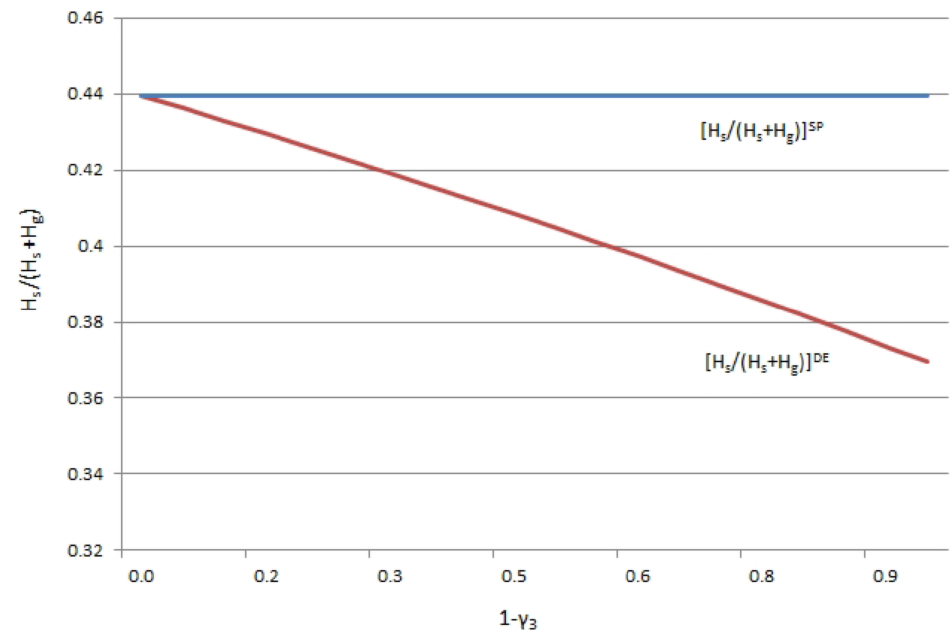
Focusing on the most interesting comparative statics, according to Table 3.1, the share of specific human capital u_s^s increases with γ_3. This happens since higher γ_3 implies a higher internalized benefit from R&D and, thus, a higher value of specific human capital. This is also the reason why the ratio of specific and general human capitals $\frac{H_s}{H_g}$, thus the share of specific human capital $\frac{H_s}{H_g+H_s}$, increases with γ_3. Meanwhile, the growth rate g increases with γ_3 since the driver of growth in this economy is the accumulation of specific human capital. Figure 3.2 illustrates the behavior of the share of specific human capital in the decentralized equilibrium as γ_3 declines.

The relation between $\frac{H_s}{H_s+H_g}$ and γ_3, when the latter declines, matches the trend in the data for the Czech Republic (see Figure 3.1) and seems to be a plausible explanation for that trend. The intuition behind this is that more centralized mechanisms are, arguably, better at accounting for possible externalities. The transition process to a market/a more decentralized economy in the Czech Republic, therefore, would have increased the effective degree of externalities, $1 - \gamma_3$.

According to Table 3.1, another seemingly reasonable explanation for the decline in the share of specific human capital $\frac{H_s}{H_s+H_g}$ can be the increase in the efficiency of the education process of general human capital λ_g for a given λ_s. Such an explanation is plausible to the extent that the introduction and use of information and communication technologies have increased the productivity of the education process in the Computing field relative to other fields. Meanwhile, our data suggest that almost all graduates in this field have general human capital.

These comparative statics can be interpreted as unexpected shocks to the economy,

Figure 3.2: *The Share of Specific Human Capital and R&D Externality*



Note: $[Hs/(H_s + H_g)]^{DE}$ is the share of specific human capital in decentralized equilibrium, and $[Hs/(H_s + H_g)]^{SP}$ is the social planner's choice for the share of specific human capital.

which induce it to adjust to a new balanced growth path with different human capital portfolio. It is worth noting that, depending on the stocks of human capital H_s and H_g and on the magnitude of the shocks, the economy can stop accumulating one of the types of human capital during this transition.

In this respect, if the economy starts with a share of specific human capital higher than the balanced growth path value then the share of specific human capital declines during the transition. This can be another explanation for the observed trend in the data for the Czech Republic. Such an explanation can be plausible when the centralized economy involved frictions and over-accumulated specific human capital (Appendix T.2 analyzes transition dynamics).

Policy Inference

Clearly, when $\gamma_3 = 1$ and the tax rates are zero, the decentralized equilibrium solution coincides with the social planner's solution. However, when $\gamma_3 < 1$ in the decentralized equilibrium the benefits from allocating specific human capital to the education sector that stems from the increased rate of innovation cannot be fully appropriated by the household. This distortion arises because of the decreasing returns in education at the individual level. As a result, for any u_s^s, specific human capital earns higher returns in social optimum than in the decentralized equilibrium. Thus, at least on the balanced growth path, the socially optimal growth rate and the share of specific human capital are all higher than their counterparts in the decentralized economy.

Proposition 3. *The policy in the decentralized equilibrium that delivers the same allocations and growth rates as in the social planner's solution is*

$$1 + \tau_Y^s = \gamma_3, \tag{3.28}$$

$$1 + \tau_Y^g = 1 + \tau_Y^s. \tag{3.29}$$

Under this policy,

$$q_4 \gamma_3 = q_4^{SP},$$

where SP stands for the social planner's solution.

Proof. See Appendix T.3. □

This result is intuitive. The tax rate τ_Y^s corrects the distortion in the value of allocating specific human capital to its accumulation that stems from an increase in the innovation rate. It equates the shadow value of specific human capital in the decentralized equilibrium adjusted for the externality $q_4\gamma_3$ to the shadow value in the social optimum q_4^{SP}. Meanwhile, the tax rate τ_Y^g is such that it keeps the optimal rule (3.22) in accordance with the socially optimal rule, where there are no tax rates. The reason why τ_Y^g and τ_Y^s need to be equal is that there are no frictions in the production side; therefore, the ratio of wages is not distorted. Such a horizontal education policy, therefore, retains the optimal ratio. However, it reduces the value of the specific human capital less than the value of the general human capital since the former also conducts R&D. Given the nature of the externalities, such a disproportionate change is essential for attaining socially optimal outcomes.

Discussion of the Model

As noted in the introduction, for the sake of highlighting the role of specific human capital as the engine of growth in the most parsimonious way, we built a model that does not capture the inherent flexibility of general human capital. This implies that our findings regarding the benefits from accumulating specific human capital are biased upwards. However, our present framework still captures how the choice of the type of human capital is tied to a choice between current and future consumption levels: The higher the utility cost is of sacrificing present consumption, the more likely the economy would be relatively abundant in general human capital.

In this respect, we view the present model as the first step towards building a generalized theoretical framework that would capture more aspects of the economic environment. Importantly, this would involve, first, building a multi-sector production structure and second, adding sources of aggregate uncertainty. The former allows us to model explicitly the defining feature of general human capital, i.e., its usability across a variety of production sectors. The latter allows us to analyze explicitly the advantage of general human capital over specific one, namely its ability to adjust to new economic conditions. Such a framework would necessarily complicate the inter-temporal trade-off between the two types of human capital to a significant degree, making growth and welfare implications non-straightforward. Our conjecture is that for highly stable economic environments, the results would be qualitatively similar to those of our present model. This extension is left for future research.

3.5 Conclusions

In this paper, we consider industry-specificity as a distinct source of human capital heterogeneity that is defined irrespective of the skill-level accumulated through education. Accordingly, we define general and specific human capital. We apply our definitions to study the composition of the production structure and education in the Czech Republic in terms of the two types of human capital and find a declining employment (use) share of specific human capital in the Czech economy.

Moreover, we develop a stylized model that captures trade-offs between the two types of human capital and the importance of specific human capital as the source of long-run growth. Through the lens of the model, we may interpret the declining share of specific human capital as an aspect of transition from the previous centralized system of education and production to a market-based mechanism.

In an environment with frictions in R&D, we discuss optimal educational policies. Our model suggests that providing public funds for R&D and education could be optimal in the presence of the R&D externality, which corresponds to a common policy implication in endogenous growth models with externalities. More empirical work is needed to establish the position of the Czech and European economies with respect to an optimal specific human capital share.

Tables

Table 3.2: *Czech LFS Sample Population Labor Status*

Status	Number of people	Percentage out of total
Employed	454110	63.72
Unemployed	31853	4.47
Out of labor force	226748	31.81
Total	712711	100

Table 3.3: *ISCED-97 Classification*

Education field	Code	Education level	Code
General Programs	01	Pre-primary education	0
Literacy and Numeracy	08	Primary education or first stage of basic education	1
Personal Skills	09		
Teacher Training and Educational Science	14	Lower secondary or second stage of basic education	2
Arts	21	(Upper) Secondary education	3
Humanities	22	Post-secondary non-tertiary education	4
Social and Behavioral Science	31	First stage of tertiary education (not leading directly to an advanced research qualification)	5
Journalism and Information	32		
Business and Administration	34		
Law	38	Second stage of tertiary education (leading to an advanced research qualification)	6
Life Science	42		
Physical Science	44		
Mathematics and Statistics	46		
Computing	48		
Engineering and Engineering Trades	52		
Manufacturing and Processing	54		
Architecture and Building	58		
Agriculture, Forestry and Fishery	62		
Veterinary	64		
Health	72		
Social Services	76		
Personal Services	81		
Environmental Protection	85		
Transport Services	84		
Security Services	86		

Table 3.4: *Industry Classification According to NACE*

Industry	Letter
Agriculture, Hunting and Related Service Activities	A
Fishing	B
Mining and Quarrying	C
Manufacturing	D
Electricity, Gas and Water Supply	E
Construction	F
Wholesale and Retail Trade; Repair of Motor Vehicles, Motorcycles and Personal and Household Goods	G
Hotels and Restaurants	H
Transport, Storage and Communication	I
Financial Intermediation	J
Real Estate, Renting and Business Activities	K
Public Administration and Defence; Compulsory Social Security	L
Education	M
Health and Social Work	N
Other Community, Social and Personal Service Activities	O
Private Households with Employed Persons	P
Extra-territorial Organizations and Bodies	Q

Table 3.5: *Classification of Occupations*

Occupation	Wide group[A]	Skill level[B]
Legislators and senior officials	1	Highly skilled white collar
Corporate managers		
Managers of small enterprises		
Physical, mathematical and engineering science professionals	2	
Life science and health professionals		
Teaching professionals		
Other professionals		
Physical and engineering associate professionals	3	
Life science and health associate professionals		
Teaching associate professionals		
Other associate professionals		
Office clerks	4	Low-skilled white collar
Customer services clerks		
Personal and protective services workers	5	
Models, salespersons and demonstrators		
Skilled agricultural and fishery workers	6	Highly skilled blue collar
Subsistence agricultural and fishery workers		
Extraction and building trades workers	7	
Metal, machinery and related trades workers		
Precision, handicraft, craft printing and related trades workers		
Other craft and related trades workers		
Stationary plant and related operators	8	Low-skilled blue collar
Machine operators and assemblers		
Drivers and mobile plant operators		
Sales and services elementary occupations	9	
Agricultural, fishery and related laborers		
Laborers in mining, construction, manufacturing and transport		

Note: A - classification according to ISCO-88; B - division according to OECD (2010).

Table 3.6: *Correlation Across Concentration Statistics*

	CI	CV	HI	EI	EXI	GI
CV	0.955	1				
HI	0.936	0.991	1			
EI	-0.869	-0.830	-0.823	1		
EXI	0.861	0.831	0.850	-0.926	1	
GI	0.919	0.979	0.950	-0.831	0.787	1

Note: CI - concentration index; CV - coefficient of variation; HI - Herfindahl index; EI - entropy index; EXI - exponential index; GI - Gini index.

Table 3.7: *Assignment of Occupations into Specific and General Human Capital Types*

Occupation	Specific = 1; General = 0	Average CI
Legislators and senior officials	1	1
Life science and health professionals	1	1
Teaching professionals	1	1
Life science and health associate professionals	1	0.6
Teaching associate professionals	1	1
Models, salespersons and demonstrators	1	1
Skilled agricultural and fishery workers	1	1
Subsistence agricultural and fishery workers	1	1
Extraction and building trades workers	1	0.6
Precision, handicraft, craft printing and related trades workers	1	1
Other craft and related trades workers	1	1
Stationary plant and related operators	1	1
Machine operators and assemblers	1	1
Agricultural, fishery and related laborers	1	1
Laborers in mining, construction, manufacturing and transport	1	0.8
Corporate managers	0	0
Managers of small enterprises	0	0
Physical, mathematical and engineering science professionals	0	0.2
Other professionals	0	0
Physical and engineering associate professionals	0	0
Other associate professionals	0	0
Office clerks	0	0
Customer services clerks	0	0.2
Personal and protective services workers	0	0
Metal, machinery and related trades workers	0	0.2
Drivers and mobile plant operators	0	0
Sales and services elementary occupations	0	0

Note: CI - concentration index.

Table 3.8: *Share of Specific Human Capital*

Industry name	NACE code	Share of specific human capital within industries, %
Fishing	B	76.0
Education	M	66.7
Agriculture, Hunting and Related Service Activities	A	60.8
Construction	F	58.1
Health and Social Work	N	57.0
Manufacturing	D	45.0
Wholesale and Retail Trade; Repair of Motor Vehicles, Motorcycles and Personal and Household Goods	G	42.7
Mining and Quarrying	C	40.4
Electricity, Gas and Water Supply	E	23.8
Public Administration and Defence; Compulsory Social Security	L	14.5
Extra-territorial Organizations and Bodies	Q	12.3
Other Community, Social and Personal Service Activities	O	11.4
Private Households with Employed Persons	P	7.7
Real Estate, Renting and Business Activities	K	5.9
Transport, Storage and Communication	I	3.8
Hotels and Restaurants	H	3.4
Financial Intermediation	J	0.6

Note: Industries are ranked by shares.

Table 3.9: *Share of Specific Human Capital within Education Fields*

Education field	Share of specific human capital within education field, %
Health	79.8
Teacher Training and Educational Science	75.1
Life Science	64.0
Manufacturing and Processing	59.9
Architecture and Building	53.2
Veterinary	47.1
Agriculture, Forestry and Fishery	43.4
Environmental Protection	36.9
Humanities	36.6
Arts	36.1
General Programs	35.4
Business and Administration	32.9
Personal Skills	32.6
Mathematics and Statistics	31.6
Physical Science	27.3
Security Services	26.8
Engineering and Engineering Trades	23.9
Personal Services	23.5
Social Services	16.8
Transport Services	12.0
Social and Behavioral Science	9.8
Journalism and Information	9.3
Computing	7.5
Law	7.3

Note: Education fields are ranked by shares. The Literacy and Numeracy field is missing from the table because we have virtually no observations for that field in the sample.

Table 3.10: *Distribution of Skill Groups Across Occupations,%*

Occupation	low-skilled ISCED-97 [0 - 2]	medium-skilled ISCED-97 [3 - 4]	highly skilled ISCED-97 [5 - 6]
Agricultural, fishery and related laborers	31.2	66.7	2.1
Sales and services elementary occupations	29.7	69.8	0.5
Laborers in mining, construction, manufacturing and transport	25.9	73.6	0.5
Skilled agricultural and fishery workers	16.4	79.6	4
Machine operators and assemblers	12.2	87.4	0.5
Stationary plant and related operators	12	87.2	0.8
Other craft and related trades workers	8.8	90.6	0.7
Drivers and mobile plant operators	8.3	91.1	0.5
Models, salespersons and demonstrators	7.7	90.8	1.5
Personal and protective services workers	7.2	90.3	2.5
Office clerks	4.7	90.6	4.7
Customer services clerks	4.6	92.6	2.9
Extraction and building trades workers	4.4	94.9	0.7
Precision, handicraft, craft printing and related trades workers	3.7	94	2.3
Metal, machinery and related related trades workers	3.7	95.6	0.7
Managers of small enterprises	2.2	67.5	30.3
Physical and engineering associate professionals	1.3	82.4	16.3
Other associate professionals	1.1	80.7	18.2
Corporate managers	1	58.1	40.8
Life science and health associate professionals	0.2	87.8	12
Other professionals	0.2	44.1	55.7
Physical, mathematical and engineering science professionals	0.1	29.6	70.3
Legislators and senior officials	0	45.7	54.3
Life science and health professionals	0	7.6	92.4
Teaching professionals	0	18.3	81.7
Teaching associate professionals	0	79.2	20.8
Subsistence agricultural and fishery workers	0	100	0

Note: Occupations are ranked by shares of low-skilled.

Table 3.11: *Distribution of Skill Groups Across Specific and General Types of Human Capital, %*

Human capital type	low-skilled ISCED-97 [0 - 2]	medium-skilled ISCED-97 [3 - 4]	highly skilled ISCED-97 [5 - 6]
Specific	8.1	78.2	13.7
General	4.8	79.6	15.6

Appendix

Appendix D.1

We use two main data sources:

1. The Czech Labor Force Survey (LFS), quarter 2, 2007. All statistics are adjusted to represent the population of the Czech labor force. At the time of the survey, 50% of total population was in the labor force of which 5.29% were unemployed. From the survey we recover information on the number of workers in the labor force (currently employed or unemployed), their education level and education field (ISCED-97), occupation (ISCO-88) and the industry (1-digit NACE) in which they are employed. The complete lists of the respective classifications can be found in Tables 3.3-3.5.

2. EUROSTAT 2007 data for the Czech Republic, Germany and the Euro area. We look into the number of all graduates from education levels ISCED-97 3-6 by field of education.

Appendix D.2

The Czech LFS data are used to calculate the number of employed individuals in each occupation (2-digit ISCO-88)-industry (1-digit NACE) cell. Given this matrix, we calculate the *within-occupation employment share across industries, within-industry employment shares across occupations*, and *total employment shares* by occupation.

The within-occupation employment shares distribution is used to calculate a number of concentration statistics. Their information is summarized into an average index that increases with the concentration of an occupation across industries. The correlations across the different concentration statistics employed are presented in Table 3.6. The ranking of the different occupations in terms of that index is summarized in Table 3.7. An occupation is classified as specific human capital if the index is greater than an overall threshold, which is set to 0.5.[18] Using this threshold, the specific human capital includes occupations related to life science, teaching and health professionals, legislators, skilled agricultural and handicraft workers.

Table 3.8 presents the within-industry employment shares for specific human capital occupations out of total industry labor input in terms of the absolute number of employees. Industries are ranked from the highest to the lowest intensity in specific human capital. The most intensive (above median) users of specific human capital are Agriculture and Fishing, Health and Social Work, Education and Manufacturing, and Mining and Construction industries. At the other end of the spectrum, occupations that relate to basic services skills are rather evenly employed across different industries and accordingly the services industries employ mostly general human capital.

We further identify how the workers' background in terms of educational fields map onto occupations in the labor market. We use Czech LFS to calculate the number of employees in each occupation (2-digit ISCO-88)-education field (2-digit ISCED-97) cell. We calculate the within-education field total allocation of employees across different occupations. We summarize the information by the within-education field total share of employees in specific human capital occupations (as defined in Table 3.7). Table 3.9 ranks education fields from the ones whose graduates mostly work as specific human capital, like Health and Teacher Training and Educational Science, to the ones whose graduates mostly work as general human capital, like Law and Computing. The median field results in producing 33% specific human capital among its graduates. We identify the group of fields whose majority of graduates (more than 50%) work as specific human capital. This implies the following highly intensive in specific human capital-producing education fields: Architecture and Building, Health, Life Science, Manufacturing and

[18] Using alternative thresholds, like the median or approximately the 30th percentile would not change the findings so drastically even though employing a more slack definition for the classification of occupations as specific human capital, of course, increases the total employment rate of the group.

Processing, and Teacher Training and Educational Science. This group of education fields alone produces 52% of all specific human capital in the economy.

Finally, Table 3.11 summarizes the education level for the group of specific human capital occupations by reporting the within-occupation shares of those who have completed secondary education (up to level ISCED-97 3) and those with post-secondary education (levels ISCED-97 4-6). At the group level, 92% specific human capital have completed education levels above ISCED-97 3, and 95% of the general human capital. The group of legislators and senior officials, life scientists, health and teaching professionals are on the top of the distribution of skills in the economy.

Specific Human Capital Among the Labor Market Entrants

We investigate the composition of new graduates, i.e., the potential new entrants into the labor force, in terms of specific and general human capital. In particular, we examine the presence of graduates among the most specific human capital intensive education fields, as identified using the Czech LFS data, using the EUROSTAT educational data for 2007 and 2000. Data from EUROSTAT, particularly for 2000, are taken with precaution, and results are summarized in Section 2.

Appendix T.1

From the accumulation processes of the two types of human capital (3.6) and (3.7), technology (3.8) and the expression for physical capital (3.9) and δ (3.10), it follows that on a balanced growth path

$$g_{H_s} = g_{H_g} = g_K = g_\Lambda \equiv g.$$

In turn, from the production function of final goods (3.1), optimal rules of the representative final goods producer (3.3), (3.4), and (3.5), the budget constraint of the household (3.12), and the balanced government budget condition (3.13), it follows that on a balanced growth path

$$\begin{aligned} g_Y &= g_C = g_T = g, \\ g_{w_s} &= g_{w_g} = g_r = 0. \end{aligned} \tag{3.30}$$

Given that all quantities grow at the same rate from (3.16)-(3.20), it follows that

$$g_{q_1} = g_{q_2} = g_{q_3} = g_{q_4} \equiv g_q. \tag{3.31}$$

This expression states that on a balanced growth path the returns on the accumulation of all types of asset holdings are equal.

From (3.30), (3.31), and (3.21) in turn, it follows that

$$g = \frac{1}{\theta}\left(\lambda_s + \lambda_\Lambda \gamma_3 \frac{q_4}{q_2} - \rho\right).$$

The System of Equations that Solves for the Growth Rates and (Relative) Allocations on Balanced Growth Path

From the production function of final goods (3.1) and the optimal rules of final goods producers (3.4), (3.3), and (3.5), it follows that

$$\frac{Y}{H_g} = \lambda_Y \left[\left(u_Y^s \frac{H_s}{H_g}\right)^{\gamma_2} \left(\frac{K}{H_g}\right)^{1-\gamma_2}\right]^{1-\gamma_1}, \tag{3.32}$$

$$w_g = \gamma_1 \frac{Y}{H_g}, \tag{3.33}$$

$$w_s = (1-\gamma_1)\,\gamma_2 \frac{1}{u_Y^s} \frac{Y}{H_s}, \tag{3.34}$$

$$\frac{Y}{r\Lambda} = \frac{1}{(1-\gamma_1)(1-\gamma_2)}. \tag{3.35}$$

From the accumulation processes of human capitals (3.6), (3.7), and ideas (3.8) and from the expression for physical capital (3.9), it follows that

$$g = \lambda_s u_s^s = \lambda_g u_g^s \frac{H_s}{H_g} = \lambda_\Lambda u_s^s \frac{H_s}{\Lambda}, \tag{3.36}$$

$$\frac{K}{\Lambda} = 1. \tag{3.37}$$

From the budget constraint (3.12) and the equation for shares of specific human capital (3.14), it follows that

$$\frac{C}{H_s} = \frac{Y}{H_s}, \tag{3.38}$$

$$1 = u_Y^s + u_s^s + u_g^s. \tag{3.39}$$

Finally, from (3.15) and (3.31) together with (3.30), it follows that

$$g = -\frac{1}{\theta} g_q, \tag{3.40}$$

and

$$-g_q = \lambda_s + \lambda_\Lambda \gamma_3 \frac{q_4}{q_2} - \rho \tag{3.41}$$

$$= \lambda_g \frac{1+\tau_Y^g}{1+\tau_Y^s} \frac{\gamma_1}{(1-\gamma_1)\gamma_2} \frac{H_s}{H_g} u_Y^s - \rho \tag{3.42}$$

$$= \frac{1-\gamma_2}{\gamma_2} \frac{1}{1+\tau_Y^s} \frac{H_s}{\Lambda} u_Y^s \left(\lambda_s \frac{q_2}{q_4} + \gamma_3 \lambda_\Lambda\right) - \rho.$$

The system of equations (3.32)-(3.42) can be solved for balanced growth path (relative) allocations and growth rates.

By elimination this system can be reduced to:

$$u_g^s = \frac{\Gamma_1 g \left(1 - \frac{1}{\lambda_s} g\right)}{(\theta + \Gamma_1) g + \rho}, \tag{3.43}$$

$$\theta g = \lambda_s + \lambda_\Lambda \gamma_3 \frac{q_4}{q_2} - \rho, \tag{3.44}$$

$$(\theta + \Gamma_1) g = \Gamma_2 \left(\lambda_s \frac{q_2}{q_4} + \gamma_3 \lambda_\Lambda\right) \left(1 - \frac{1}{\lambda_s} g\right) - \rho, \tag{3.45}$$

where

$$\Gamma_1 = \frac{1+\tau_Y^g}{1+\tau_Y^s} \frac{\gamma_1}{(1-\gamma_1)\gamma_2}, \tag{3.46}$$

$$\Gamma_2 = \frac{1-\gamma_2}{\gamma_2}\frac{1}{1+\tau_Y^s}\frac{\lambda_s}{\lambda_\Lambda}. \tag{3.47}$$

From the last two equations of the remaining system g can be eliminated and the resulting equation can be written as

$$a\left(\frac{q_4}{q_2}\right)^2 + b\left(\frac{q_4}{q_2}\right) + c = 0, \tag{3.48}$$

where

$$\begin{aligned}
a &= \left(\theta + \Gamma_1 + \gamma_3\frac{\lambda_\Lambda}{\lambda_s}\Gamma_2\right)\frac{1}{\theta}\lambda_\Lambda\gamma_3,\\
b &= \frac{\theta+\Gamma_1}{\theta}\left(\lambda_s - \rho\right) + \rho + \frac{\lambda_s\left(2-\theta\right)-\rho}{\theta}\gamma_3\frac{\lambda_\Lambda}{\lambda_s}\Gamma_2,\\
c &= -\Gamma_2\left[\lambda_s - \frac{1}{\theta}\left(\lambda_s-\rho\right)\right].
\end{aligned}$$

Since (3.48) is a quadratic equation in $\frac{q_4}{q_2}$, there are two solutions. If $a > 0$ and $c < 0$, the solutions are real numbers that have different signs. It can be shown that a sufficient condition for this is $\theta \geq 1$.

A similar quadratic equation can be derived for $\frac{H_s}{H_g}$ using (3.36) and (3.43)-(3.45),

$$\tilde{a}\left(\frac{H_s}{H_g}\right)^2 + \tilde{b}\left(\frac{H_s}{H_g}\right) + \tilde{c} = 0, \tag{3.49}$$

where

$$\begin{aligned}
\tilde{a} &= \left[\theta - \frac{1}{\lambda_s}\left(\lambda_s-\rho\right)\right]\lambda_g\Gamma_1,\\
\tilde{b} &= -\left[\lambda_s\theta + \left(\theta\lambda_s+\rho\right)\gamma_3\frac{\lambda_\Lambda}{\lambda_s}\Gamma_2 + \Gamma_1\left(\lambda_s-\rho\right)\right],\\
\tilde{c} &= -\frac{1}{\lambda_g}\lambda_s\rho\gamma_3\frac{\lambda_\Lambda}{\lambda_s}\Gamma_2.
\end{aligned}$$

Similar to the case for $\frac{q_4}{q_2}$, a sufficient condition for having one real and positive root is $\theta \geq 1$.

Comparative Statics

From (3.48), it is straightforward to notice that $\frac{q_4}{q_2}$ increases with ρ, does not depend on λ_g, and is inversely proportional to λ_Λ. Moreover, from (3.48) it can be shown that the sign of the derivative of $\frac{q_4}{q_2}$ with respect to γ_1 is equivalent to the sign of the following expression:

$$\left[-\left(1-\frac{b}{\sqrt{b^2-4ac}}\right)\frac{\partial}{\partial\gamma_1}b-\frac{2c}{\sqrt{b^2-4ac}}\frac{\partial}{\partial\gamma_1}a\right]a-\left[-b+\sqrt{b^2-4ac}\right]\frac{\partial}{\partial\gamma_1}a.$$

Since $a>0$, $\frac{\partial}{\partial\gamma_1}b>0$, and $\frac{\partial}{\partial\gamma_1}a>0$, it can be easily shown that this expression is negative. Therefore, $\frac{q_4}{q_2}$ declines with γ_1.

Given that $\frac{q_4}{q_2}$ does not depend on λ_g and is inversely proportional to λ_Λ, it follows from (3.36) and (3.43)-(3.45) that $\frac{H_s}{H_g}$ declines with λ_g and does not depend on λ_Λ. In turn, the signs of the derivatives of $\frac{H_s}{H_g}$ with respect to γ_1 and θ are equivalent to the signs of the following expressions.

$$\begin{aligned}&-\tilde{a}\frac{\partial}{\partial\theta}\tilde{b}+\tilde{b}\frac{\partial}{\partial\theta}\tilde{a}+\frac{2\tilde{a}\tilde{c}}{\sqrt{\tilde{b}^2-4\tilde{a}\tilde{c}}-\tilde{b}}\frac{\partial}{\partial\theta}\tilde{a},\\&-\tilde{a}\frac{\partial}{\partial\gamma_1}\tilde{b}+\tilde{b}\frac{\partial}{\partial\gamma_1}\tilde{a}+\frac{2\tilde{a}\tilde{c}}{\sqrt{\tilde{b}^2-4\tilde{a}\tilde{c}}-\tilde{b}}\frac{\partial}{\partial\gamma_1}\tilde{a}.\end{aligned}$$

These expressions are negative since $\tilde{c}<0$, $\tilde{a}\frac{\partial}{\partial\theta}\tilde{b}>\tilde{b}\frac{\partial}{\partial\theta}\tilde{a}$, and $\tilde{a}\frac{\partial}{\partial\gamma_1}\tilde{b}>\tilde{b}\frac{\partial}{\partial\gamma_1}\tilde{a}$. Therefore, $\frac{H_s}{H_g}$ declines with γ_1 and θ.

Meanwhile, since

$$\begin{aligned}&\frac{\partial}{\partial\gamma_3}\tilde{b}<0,\\&\frac{\partial}{\partial\gamma_3}\tilde{c}<0,\\&\frac{\partial}{\partial\gamma_3}\tilde{a}=0,\\&\frac{\partial}{\partial\lambda_s}\tilde{b}<0,\\&\frac{\partial}{\partial\lambda_s}\left(\tilde{a}\tilde{c}\right)<0,\\&\frac{\partial}{\partial\lambda_s}\tilde{a}<0,\end{aligned}$$

from (3.49) it follows that $\frac{H_s}{H_g}$ increases with γ_3 and λ_s.

When $\tau_Y^g\equiv\tau_Y^s$ it can be shown that

$$\frac{\partial}{\partial\tau_Y^s}\tilde{b},\frac{\partial}{\partial\tau_Y^s}\tilde{c}<0;\frac{\partial}{\partial\tau_Y^s}\tilde{a}=0.$$

From (3.49) it then follows that in this case $\frac{H_s}{H_g}$ declines with τ_Y^s. According to (3.36), the ratio of specific human capital to physical human capital $\frac{H_s}{\Lambda}$ depends only on λ_s and λ_Λ. It increases with λ_s and declines with λ_Λ.

These results together with (3.36) and (3.43)-(3.45) imply the following signs of comparative statics:

Table 3.12: *Analytical Comparative Statics*

	q_4/q_2	q_3/q_2	H_s/H_g	H_s/Λ	g	u_s^s	u_g^s	u_Y^s	u_s^s/u_g^s
ρ	$+$	$+$		0					
θ			$-$	0	$-$	$-$			$-$
γ_1	$-$	$-$	$-$	0	$-$	$-$			
γ_2				0					
γ_3			$+$	0	$+$	$+$			$+$
λ_s			$+$	$+$					
λ_g	0	$-$	$-$	0	0	0	0	0	0
$\lambda_s, \lambda_s \equiv \lambda_g$				$+$					
λ_Λ	$-$	0	0	$-$	0	0	0	0	0
τ_Y^s				0					
$\tau_Y^s, \tau_Y^g \equiv \tau_Y^s$	$-$	$-$	$-$	0	$-$	$-$			$-$

Note: The sign $+$ means a positive relationship, $-$ negative, and 0 means no relationship.

Deriving the signs of the remaining comparative statics requires tedious algebra. Numerical methods are used in order to obtain them. These additional results, together with the intervals of parameter values used in the numerical exercises, are presented in Table 3.1.

Appendix T.2

Denote

$$\omega_1 = \frac{H_g}{H_s},$$
$$\omega_2 = \frac{\Lambda}{H_s}.$$

In the case of an interior solution for the shares of specific human capital [i.e., $u_s^s, u_g^s, u_Y^s \in (0,1)$], it can be shown that the dynamic system of equations of the model reduces to two differential equations from u_Y^s and ω_2. These equations are

$$\begin{pmatrix} g_{u_Y^s} \\ g_{\omega_2} \end{pmatrix} = \frac{1}{\det A(u_Y^s, \omega_2)} \begin{pmatrix} A_{22}b_1 - A_{12}b_2 \\ A_{11}b_2 - A_{21}b_1 \end{pmatrix}, \tag{3.50}$$

where

$$\det A(u_Y^s, \omega_2) = A_{11}A_{22} - A_{12}A_{21},$$
$$A_{11} = \frac{\lambda_\Lambda - \lambda_s\omega_2}{\omega_2}\frac{1}{\lambda_g}\frac{\frac{\lambda_g}{\lambda_s}\Gamma_1 u_Y^s}{1+\gamma_3\frac{\lambda_\Lambda}{\lambda_s}\frac{\lambda_\Lambda}{\lambda_s}\Gamma_2\frac{1}{\omega_2}u_Y^s}\frac{1}{1+\gamma_3\frac{\lambda_\Lambda}{\lambda_s}\frac{\lambda_\Lambda}{\lambda_s}\Gamma_2\frac{1}{\omega_2}u_Y^s},$$
$$A_{12} = 1 + \frac{\Gamma_1 u_Y^s}{1+\gamma_3\frac{\lambda_\Lambda}{\lambda_s}\frac{\lambda_\Lambda}{\lambda_s}\Gamma_2\frac{1}{\omega_2}u_Y^s} + \gamma_3\frac{\lambda_\Lambda}{\lambda_s}\frac{\lambda_\Lambda}{\lambda_s}\Gamma_2\frac{1}{\omega_2}u_Y^s A_{11},$$
$$A_{21} = \frac{\lambda_\Lambda - \lambda_s\omega_2}{\omega_2}\left[1 + (\theta-1)(1-\gamma_1)\gamma_2 + (\theta-1)\gamma_1\frac{1}{1+\gamma_3\frac{\lambda_\Lambda}{\lambda_s}\frac{\lambda_\Lambda}{\lambda_s}\Gamma_2\frac{1}{\omega_2}u_Y^s}\right],$$
$$A_{22} = \theta\frac{\lambda_\Lambda}{\omega_2} - A_{21},$$
$$b_1 = \frac{\lambda_\Lambda - \lambda_s\omega_2}{\omega_2}\left(1 - u_Y^s\right),$$
$$b_2 = \frac{\lambda_\Lambda - \lambda_s\omega_2}{\omega_2}\left[\lambda_s\left(1+\gamma_3\frac{\lambda_\Lambda}{\lambda_s}\frac{\lambda_\Lambda}{\lambda_s}\Gamma_2\frac{1}{\omega_2}u_Y^s\right) - \rho\right].$$

Therefore, the Jacobian of the system is a two-by-two matrix, and its elements are

$$J(1,1) = \frac{1}{\det A(u_Y^s,\omega_2)}\frac{\partial}{\partial u_Y^s}\left(A_{22}b_1 - A_{12}b_2\right) - \left[\frac{1}{\det A(u_Y^s,\omega_2)}\right]^2\left(A_{22}b_1 - A_{12}b_2\right)\frac{\partial}{\partial u_Y^s}\det A(u_Y^s,\omega_2),$$
$$J(1,2) = \frac{1}{\det A(u_Y^s,\omega_2)}\frac{\partial}{\partial \omega_2}\left(A_{22}b_1 - A_{12}b_2\right) - \left[\frac{1}{\det A(u_Y^s,\omega_2)}\right]^2\left(A_{22}b_1 - A_{12}b_2\right)\frac{\partial}{\partial \omega_2}\det A(u_Y^s,\omega_2),$$

$$J(2,1) = \frac{1}{\det A(u_Y^s,\omega_2)} \frac{\partial}{\partial u_Y^s} (A_{11}b_2 - A_{21}b_1)$$
$$- \left[\frac{1}{\det A(u_Y^s,\omega_2)}\right]^2 (A_{11}b_2 - A_{21}b_1) \frac{\partial}{\partial u_Y^s} \det A(u_Y^s,\omega_2),$$
$$J(2,2) = \frac{1}{\det A(u_Y^s,\omega_2)} \frac{\partial}{\partial \omega_2} (A_{11}b_2 - A_{21}b_1)$$
$$- \left[\frac{1}{\det A(u_Y^s,\omega_2)}\right]^2 (A_{11}b_2 - A_{21}b_1) \frac{\partial}{\partial \omega_2} \det A(u_Y^s,\omega_2).$$

It is straightforward to notice that $\det A(u_Y^s,\omega_2)$ is proportional to $\frac{\lambda_\Lambda - \lambda_s\omega_2}{\omega_2}$. In turn, $(A_{11}b_2 - A_{21}b_1)$ is proportional to the square of $\frac{\lambda_\Lambda - \lambda_s\omega_2}{\omega_2}$. At the steady-state (balanced growth path), where

$$u_Y^s = 1 - \frac{\Gamma_1\left(1 - \frac{g}{\lambda_s}\right)}{(\theta + \Gamma_1) g + \rho} g - \frac{1}{\lambda_s} g,$$
$$\omega_2 = \frac{\lambda_\Lambda}{\lambda_s},$$
$$\begin{pmatrix} 0 \\ 0 \end{pmatrix} = \frac{1}{\det A} \begin{pmatrix} A_{22}b_1 - A_{12}b_2 \\ A_{11}b_2 - A_{21}b_1 \end{pmatrix},$$

this implies that

$$\frac{\partial}{\partial u_Y^s} g_{\omega_2} = 0.$$

Therefore, the eigenvalues of the Jacobian matrix at the steady-state are $J(1,1)$ and $J(2,2)$.

After some tedious calculus, it can be shown that at the steady-state

$$J(2,2) < 0,$$

and $J(1,1)$ is positive if the determinant of matrix A is negative. The determinant of matrix A is negative if

$$\left\{(\theta-1)(1-\gamma_1)(1-\gamma_2) - \gamma_3 \frac{\lambda_\Lambda}{\lambda_s} \Gamma_2 \left[1 + (\theta-1)(1-\gamma_1)\gamma_2\right] u_Y^s\right\} \Gamma_1 u_Y^s$$
$$- \left(1 + \gamma_3 \frac{\lambda_\Lambda}{\lambda_s} \Gamma_2 u_Y^s\right) \left\{\left[1 + (\theta-1)(1-\gamma_1)\gamma_2\right] \left(1 + \gamma_3 \frac{\lambda_\Lambda}{\lambda_s} \Gamma_2 u_Y^s\right) + (\theta-1)\gamma_1\right\}$$
$$< 0,$$

where u_Y^s is given by (3.36) and (3.39).

Since $u_Y^s \in (0,1)$ a sufficient condition for saddle path stability is

$$\left[(1-\gamma_2)\frac{\gamma_1}{\gamma_2}\frac{1+\tau_Y^g}{1+\tau_Y^s} - (1-\gamma_1)\gamma_2 - \gamma_1\right] < \frac{1}{\theta-1}.$$

When tax rates τ_Y^s and τ_Y^g are equated, this condition can be rewritten as

$$(1-\gamma_2)^2\frac{\gamma_1}{\gamma_2} - \gamma_2 < \frac{1}{\theta-1},$$

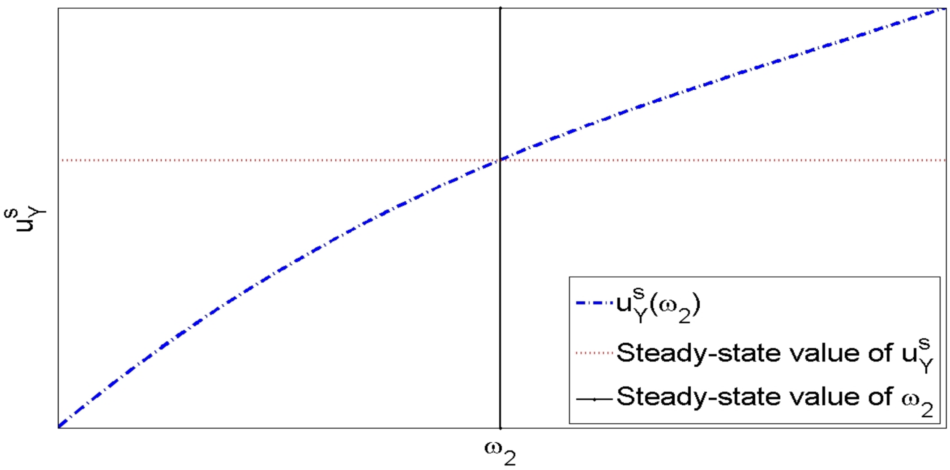
and holds, for example, for $\gamma_2 > 0.5$ or for $\theta = 1$.

If the initial value of the ratio of human capital types ω_2 is not at its steady-state, the model exhibits transition dynamics along the stable manifold. At time 0, the value of u_Y^s jumps to the stable-manifold level, after which a monotonic convergence of u_Y^s, ω_2, as well as ω_1 to their steady-state values is observed.

Figure 3.3 presents the stable manifold in (u_Y^s, ω_2) space for the following parameter values:

$$\begin{aligned}&\rho = 0.05, \theta = 1, \gamma_1 = 0.3, \gamma_2 = 0.5, \gamma_3 = 0.1, \\ &\lambda_s = 0.1, \lambda_g = 0.1, \lambda_\Lambda = 0.1, \tau_Y^s = \tau_Y^g.\end{aligned} \tag{3.51}$$

Figure 3.3: *The Stable Manifold in* (u_Y^s, ω_2) *Space*



Note: This figure offers the simulated stable manifold in (u_Y^s, ω_2) space.

It might happen that the initial value of general human capital is such that either u_s^s or u_g^s hits zero bound.[19]

For example, suppose that $u_s^s > 0$ and $u_g^s = 0$. In this case,

$$\lambda_g q_3 < \lambda_s q_2 + \gamma_3 \lambda_\Lambda q_4. \tag{3.52}$$

[19] Given that (3.1) satisfies Inada conditions, it has to be that $u_Y^s > 0$.

Since the wage of general human capital w_g, Eq. (3.3), increases relative to the wage of specific human capital w_s, Eq. (3.4) and the return on physical capital r, Eq. (3.5), as H_s and K grow, at some point in time w_g will become so large that u_g^s will become positive. This is equivalent to a declining q_2 and q_4 and a constant q_3 in (3.52) and can hold if the economy is relatively abundant in general human capital. Such a situation holds, for example, when $\omega_1 \geq 1$, $\theta = 5$, and the remaining parameters are given by (3.51).

Similarly, when $u_s^s = 0$ and $u_g^s > 0$

$$\lambda_g q_3 > \lambda_s q_2 + \gamma_3 \lambda_\Lambda q_4. \tag{3.53}$$

In this case, since w_s and r increase relative to w_g as H_g grows at some point in time, u_s^s will become positive. This is equivalent to a declining q_3 and a constant q_2 and q_4 in (3.53) and can hold if the economy is relatively abundant in specific human capital. Such a situation holds, for example, when $\omega_1 \leq 0.2$ and for parameter values (3.51).

Appendix T.3

It can be shown that in the social optimum, the quadratic equation (3.48) is given by

$$\left(\frac{\theta+\tilde{\Gamma}_1}{\theta}+\tilde{\Gamma}_2\frac{\lambda_\Lambda}{\lambda_s}\frac{1}{\theta}\right)\lambda_\Lambda\left(\frac{q_4}{q_2}\right)^2+ \\ +\left[\frac{\theta+\tilde{\Gamma}_1}{\theta}\left(\lambda_s-\rho\right)+\rho+\frac{\lambda_s\left(1-\theta\right)+\lambda_s-\rho}{\lambda_s\theta}\tilde{\Gamma}_2\lambda_\Lambda\right]\frac{q_4}{q_2}- \\ -\tilde{\Gamma}_2\left[\lambda_s-\frac{1}{\theta}\left(\lambda_s-\rho\right)\right]=0, \tag{3.54}$$

where $\tilde{\Gamma}_1$ and $\tilde{\Gamma}_2$ are given by (3.46) and (3.47) with the tax rates τ_Y^s and τ_Y^g set to zero. This implies that when the tax rates in the decentralized equilibrium are set so that

$$1+\tau_Y^s=\gamma_3, \tag{3.55}$$

$$1+\tau_Y^g=1+\tau_Y^s, \tag{3.56}$$

(thus making $\tilde{\Gamma}_1=\Gamma_1$ and $\tilde{\Gamma}_2=\gamma_3\Gamma_2$), the positive root of (3.54) coincides with γ_3 times the positive root of (3.48). In other words,

$$\gamma_3\frac{q_4}{q_2}=\left(\frac{q_4}{q_2}\right)^{SP}, \tag{3.57}$$

where SP denotes the social planner's solution.

Moreover, it can be easily shown that the system of equations which solves for the balanced growth path allocations and growth rates of social optimum is essentially the same as (3.32)-(3.42), except that γ_3 is equal to 1 in (3.42). Therefore, it can be shown that the policy (3.55) and (3.56) delivers socially optimal allocations and growth rates in the decentralized equilibrium on the balanced growth path. According to (3.50), it also does so on the transition path.

Appendix E.1

In this section, we offer the decentralized equilibrium results when $\gamma_3 = 0$.

The problem and optimal decision rules of the final goods producer and the human capital accumulation processes remain the same. Therefore, the expressions (3.1)-(3.7) are still valid. When $\gamma_3 = 0$, the accumulation of technology is a pure externality for the household. Therefore, the household's problem is

$$\begin{aligned}
&\max_{u_Y^s, u_g^s, C} \int_0^{+\infty} \frac{C_t^{1-\theta} - 1}{1-\theta} \exp(-\rho t)\, dt \\
&s.t. \\
&(3.12), (3.6), (3.7), (3.14), \\
&H_s(0), H_g(0), K(0) > 0 - \textit{given.}
\end{aligned}$$

Assigning shadow values $\{q_i\}$ to constraints (3.12), (3.6), (3.7), the decision rules that follow from the household's optimization are

$$C^{-\theta} = q_1,$$

$$q_1 w_s (1 + \tau_Y^s) H_s = q_2 \frac{\dot{H}_s}{u_s^s}, \tag{3.58}$$

$$q_3 \frac{\dot{H}_g}{u_g^s} = q_2 \frac{\dot{H}_s}{u_s^s}, \tag{3.59}$$

$$q_1 r > 0 \Rightarrow \text{supply all } K,$$

$$\dot{q}_2 = q_2 \rho - \left[q_1 w_s u_Y^s (1 + \tau_Y^s) + q_2 \frac{\dot{H}_s}{H_s} + q_3 \frac{\dot{H}_g}{H_s} \right], \tag{3.60}$$

$$\dot{q}_3 = q_3 \rho - q_1 w_g (1 + \tau_Y^g). \tag{3.61}$$

From (3.6), (3.7), (3.58), (3.59), (3.60), and (3.61), it follows that

$$\begin{aligned}
&\frac{q_3}{q_2} = \frac{\lambda_s}{\lambda_g}, \\
&- g_{q_2} = \lambda_s - \rho, \\
&- g_{q_3} = \lambda_g \frac{w_g (1 + \tau_Y^g)}{w_s (1 + \tau_Y^s)} - \rho.
\end{aligned}$$

This implies that when both types of human capital are accumulated, the ratio of wages should be fixed

$$\frac{w_g (1 + \tau_Y^g)}{w_s (1 + \tau_Y^s)} = \frac{\lambda_s}{\lambda_g}.$$

The economy is on a balanced growth path in such a case. The growth rate of the economy (quantities) on a balanced growth path is

$$g = \frac{1}{\theta}(\lambda_s - \rho).$$

The growth rate above is less than the socially optimal one, given by the equation (3.26) with γ_3 set to one. Therefore, the share of the specific human capital allocated to its accumulation is lower than its socially optimal value, because u_s^s is proportional to the growth rate of H_s and all the quantities are growing at the same rate.

The comparative statics for this model can be derived analytically and are presented in Table 3.13.

Table 3.13: *Comparative Statics*

	q_3/q_2	H_s/H_g	H_s/Λ	g	u_s^s	u_g^s	u_Y^s	u_s^s/u_g^s
ρ	0	$-$	0	$-$	$-$	$\pm$	$+$	$-$
θ	0	$-$	0	$-$	$-$	$\pm$	$+$	$-$
γ_1	0	$-$	0	0	0	$+$	$-$	$-$
γ_2	0	$+$	0	0	0	$-$	$+$	$+$
λ_s	$+$	$+$	$+$	$+$	$+$	$\pm$	$-$	$+$
λ_g	$-$	$-$	0	0	0	0	0	0
$\lambda_s, \lambda_s \equiv \lambda_g$	0	$+$	$+$	$+$	$+$	$\pm$	$-$	$+$
λ_Λ	0	0	$-$	0	0	0	0	0
τ_Y^s	0	$+$	0	0	0	$-$	$+$	$+$
$\tau_Y^s, \tau_Y^g \equiv \tau_Y^s$	0	0	0	0	0	0	0	0

Note: The sign $+$ means a positive relationship, $-$ negative, 0 no relationship, and $\pm$ means that the relationship depends on model parameters.

For example, u_g^s increases with ρ and θ when $\theta = 1$ and $\lambda_s > 2\rho$ and declines with these parameters when $\theta >> 1$. Meanwhile, u_g^s increases with λ_s when $\theta >> 1$ and $\lambda_s < 2\rho$ and declines when $\lambda_s > 2\rho$.

Appendix E.2

In this section, we offer the decentralized equilibrium results when R&D intensity is a choice variable.

Similarly to Appendix E.1, the problem and optimal decision rules of the final goods producer and the human capital accumulation processes remain the same. Therefore, the expressions (3.1)-(3.7) are still valid. However, the R&D equation and the equation for shares of specific human capital change. The household's problem in such a case is

$$\begin{aligned}
&\max_{u_Y^s, u_g^s, C} \int_0^{+\infty} \frac{C_t^{1-\theta}-1}{1-\theta} \exp\left(-\rho t\right) dt \\
&s.t. \\
&(3.12), (3.6), (3.7), \\
&\dot{\Lambda} = \delta \left(u_\Lambda^s H_s\right)^{\gamma_3}, \qquad (3.62) \\
&u_s^s + u_Y^s + u_g^s + u_\Lambda^s \leq 1, \\
&H_s(0), H_g(0), \Lambda(0) > 0 - given.
\end{aligned}$$

Assigning shadow value $\{q_i\}$ to constraints (3.12), (3.6), (3.7), and (3.62), the decision rules that follow from the household's optimization are

$$\begin{aligned}
&C^{-\theta} = q_1, \\
&q_1 w_s \left(1+\tau_Y^s\right) H_s = q_2 \frac{\dot{H}_s}{u_s^s}, \\
&q_3 \frac{\dot{H}_g}{u_g^s} = q_2 \frac{\dot{H}_s}{u_s^s}, \\
&q_4 \gamma_3 \frac{\dot{\Lambda}}{u_\Lambda^s} = q_2 \frac{\dot{H}_s}{u_s^s}, \\
&\dot{q}_2 = q_2 \rho - \left[q_1 w_s u_Y^s \left(1+\tau_Y^s\right) + q_2 \frac{\dot{H}_s}{H_s} + q_3 \frac{\dot{H}_g}{H_s} + q_4 \gamma_3 \frac{\dot{\Lambda}}{H_s} \right], \\
&\dot{q}_3 = q_3 \rho - q_1 w_g \left(1+\tau_Y^g\right), \\
&\dot{q}_4 = q_4 \rho - q_1 r k.
\end{aligned}$$

These optimal rules imply that

$$\begin{aligned}
&\frac{q_3}{q_2} = \frac{\lambda_s}{\lambda_g}, \\
&\frac{q_4}{q_2} = \frac{\lambda_s}{\gamma_3 \lambda_\Lambda}, \\
&-g_{q_2} = \lambda_s - \rho,
\end{aligned}$$

$$-g_{q_3} = \lambda_g \frac{w_g \left(1+\tau_Y^g\right)}{w_s \left(1+\tau_Y^s\right)} - \rho,$$
$$-g_{q_4} = \gamma_3 \lambda_\Lambda \frac{rk}{w_s \left(1+\tau_Y^s\right)} - \rho.$$

Therefore, on a balanced growth path the growth rate of the economy and the share of specific human capital allocation to its accumulation are

$$g = \frac{1}{\theta}\left(\lambda_s - \rho\right),$$
$$u_s^s = \frac{g}{\lambda_s}.$$

The comparative statics for this model can be derived analytically and are presented in Table 3.14.

Table 3.14: *Comparative Statics*

	q_4/q_2	q_3/q_2	H_s/H_g	H_s/Λ	g	u_s^s	u_g^s	u_Y^s	u_Λ^s	u_s^s/u_g^s
ρ	0	0	$-$	$-$	$-$	$-$	$\pm$	$+$	$\pm$	$-$
θ	0	0	$-$	$-$	$-$	$-$	$\pm$	$+$	$\pm$	$-$
γ_1	0	0	$-$	$+$	0	0	$+$	$-$	$-$	$-$
γ_2	0	0	$+$	$+$	0	0	$-$	$+$	$-$	$+$
γ_3	$-$	0	$+$	$-$	0	0	$-$	$-$	$+$	$-$
λ_s	$+$	$+$	$+$	$+$	$+$	$+$	$\pm$	$-$	$\pm$	$+$
λ_g	0	$-$	$-$	0	0	0	0	0	0	0
$\lambda_s, \lambda_s \equiv \lambda_g$	$+$	0	$+$	$+$	$+$	$+$	$\pm$	$-$	$\pm$	$+$
λ_Λ	$-$	0	0	$-$	0	0	0	0	0	0
τ_Y^s	0	0	$+$	$+$	0	0	$-$	$+$	$-$	$+$
$\tau_Y^s, \tau_Y^g \equiv \tau_Y^s$	0	0	$-$	$+$	0	0	$+$	$+$	$-$	$-$

Note: The sign $+$ means a positive relationship, $-$ negative, 0 no relationship, and $\pm$ means that the relationship depends on model parameters.

When $\theta >> 1$, $\frac{\partial}{\partial \lambda_s} u_g^s$ and $\frac{\partial}{\partial \lambda_s} u_\Lambda^s$ are both positive; these derivatives become negative when $\theta = 1$ and $\gamma_2 \approx 0$ or $\gamma_1 \approx 1$. When $\theta >> 1$, $\frac{\partial}{\partial \rho} u_g^s$ and $\frac{\partial}{\partial \rho} u_\Lambda^s$ are negative but turn positive for $\gamma_2 \approx 0$ or $\gamma_1 \approx 1$. Finally, $\frac{\partial}{\partial \theta} u_g^s$ and $\frac{\partial}{\partial \theta} u_\Lambda^s$ are negative when $\theta >> 1$, but these derivatives change sign for $\gamma_2 \approx 0$ or $\gamma_1 \approx 1$.

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