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(Citation)
神戸大学経済学研究科 Discussion Paper,905

(Issue Date)
2009-04

(Resource Type)
technical report

(Version)
Version of Record

(URL)
https://hdl.handle.net/20.500.14094/81001050

Competitive Innovation with Codified And Tacit Knowledge

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April 2009

Abstract

R&D-based models of endogenous technical progress rest on a premise that technical progress is driven by profit-seeking entrepreneurs. This literature led to a dominant view that endogenous technical advance is not consistent with perfect competition with constant returns to scale. Departing from this dominant perspective, we demonstrate that technical progress endogenously occurs in a perfectly competitive economy under constant returns to scale in rivalrous inputs. Our result is based on a hypothesis that R&D creates codified and tacit knowledge as joint products. Empirical and case studies are discussed to support the hypothesis. Using the model, we demonstrate that stronger patent protection can encourage or discourage R&D, depending on the size of an economy.

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1 Introduction

Neo-classical growth models with perfect competition are silent on determinants of technical progress. Motivated by this observation, R&D-based models of endogenous technical progress were proposed as an alternative analytical framework for long-run economic growth. Those R&D-based models rest on a central premise that technical progress is driven by profit-seeking entrepreneurs, and innovative activity is compensated by profits generated in an imperfect product market. Importantly, this influential Schumpeterian approach implies that endogenous technical advance does not occur in a perfectly competitive economy with constant returns to scale. This conclusion is widely accepted among policy makers, and behind policy discussion of intellectual property rights.[1]

This paper departs from this dominant Schumpeterian perspective, and argues that profit incentives and monopoly power are sufficient but not necessary for endogenous technical progress. We demonstrate that technical progress endogenously occurs in a perfectly competitive economy under constant returns to scale in rivalrous inputs. This result comes in stark contrast with the landmark implication of R&D-based models of endogenous growth. Our argument is based on the distinction between *codified* and *tacit* knowledge, and a hypothesis that both types of knowledge are joint products of R&D activity.[2]

Codified knowledge is detailed specifications of new technology, which is codified in a written form (e.g. manuals and journals). An example is a source code of a computer software. On the other hand, tacit knowledge is not (or even cannot be) stated in an explicit form.[3] But, it allows experts to obtain desired results without reflecting on codified knowledge. That is, tacit knowledge is ideas of how to efficiently implement codified knowledge and even create new codified knowledge. An example is a software engineer's

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[1] For examples, see a series of books titled "*Innovation Policy and the Economy*", published by MIT Press.

[2] See Polanyi (1966) who explicitly introduces the concept of tacit knowledge. Although introducing tacit knowledge into the context of innovation is not new (e.g. Nonaka and Takeuchi, 1995), our novel contribution is that tacit knowledge is explicitly incorporated into a Schumpeterian growth model to establish that endogenous technical progress occurs under perfect competition.

[3] A good example is how to ride a bicycle. People usually become able to ride a bicycle after practices rather than reading instructions. It is because of difficulty conveying an idea of how to ride a bicycle to other people in words.

programing ability developed through accumulated experiences.[4] In the joint product hypothesis, innovative activity creates codified and tacit knowledge, the latter of which is embodied in innovators. The next section discusses some examples which illustrate this hypothesis.

A defining characteristic of codified knowledge is non-rivalry. It "can be used as often as desired, in as many productive activities as desired," as Romer (1990) stresses. Due to this public-good nature, he argues that monopoly profits are required to compensate R&D inputs. This is the aspect of innovative activity that existing R&D-based models emphasize most. In a sense, tacit knowledge also plays an implicit role in those models. For example, consider the model of Romer (1990). R&D workers become more able to do research activity as new codified knowledge is created.[5] This assumption is equivalent to saying that researchers accumulate tacit knowledge which is useful in applying existing codified knowledge to create new codified knowledge. This is a plausible assumption, given that any R&D activity is a learning process. However, an assumption is made that tacit knowledge is a pure public good. It is non-rivalrous in the sense that tacit knowledge instantaneously diffuses across all workers at no cost without degrading its quality.[6] It is also non-excludable, since it is not possible for R&D workers to prevent from others benefiting from their learning experiences. Because of this public-good nature, no innovator can appropriate returns from the creation of new tacit knowledge, and monopoly profits are the only source to motivate researchers.

However, we argue that tacit knowledge has a degree of excludability, because one's ability to utilize codified knowledge and even create new codified knowledge is not automatically transmitted to other people. Such ability can be gained only through costly learning. This observation is supported by, e.g. a case study of the biotechnology industry in Zucker, Darby, and Brewer (1998) and an empirical work of Cohen and Levinthal (1989). To the extent that tacit

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[4] The relevance of distinguishing two types of knowledge is illustrated by questionnaire results reported by Jensen and Thursby (2001) regarding licensing university inventions to private firms. University technology transfer officers think that 71 percent of the inventions licensed require cooperation by the inventor for successful commercialization. Another relevant study is Darby and Zucker (2003), who argue that new high-tech industries are created around universities where inventing scientists work, because their active participation is essential for commercialization. They base their view on the study of Mowery and Ziedonis (2001) who present evidence consistent with it.

[5] The stock of knowledge A_t increases according to $\dot{A}_t = \delta t R_t$, $\delta > 0$ where R_t is the number of researchers. δt is R&D productivity that increases as new knowledge is created.

[6] If tacit knowledge has a degree of rivalry in the Romer model, an identity or work history of researchers should matter. But it is not the case in his model.

knowledge is excludable at least partially, innovators can appropriate returns from creating codified knowledge by jointly producing tacit knowledge.

Based on this insight, we propose an R&D-based growth model where researchers are motivated by an increase in returns in general over and above returns earned before innovation. Such increased returns consist of monopoly profits, if codified knowledge is excludable, and returns from the creation of tacit knowledge in the form of *intellectual human capital*.[7] In a competitive economy with zero monopoly rent, competitive returns from tacit knowledge embodied in innovators can be sufficient to compensate R&D activity, and endogenous technical progress occurs. Note that this result is compatible with constant returns to scale in rivalrous inputs where aggregate income is exhausted as factor payments. This conclusion comes in stark contrast with the landmark implication of R&D-based models of endogenous growth that endogenous technical progress is not consistent with perfectly competitive economy.[8]

At this stage it is important to discuss some differences between human capital used in existing growth models and *intellectual* human capital that accumulates due to tacit knowledge in our model. In general, human capital refers to the ability or skills to perform economic activity, and it is often assumed to accumulate through schooling, on-the-job training and learning-by-doing. Typically, those activities are broadly defined to include, e.g., primary education and productivity improvement of unskilled manual workers, which is irrelevant to the joint product hypothesis in our study. On the other hand, the accumulation of intellectual human capital requires technically more advanced learning activities, e.g. tertiary education and engaging in research. This is because tacit knowledge we consider concerns abilities to use and create new technologies. In addition, we believe that the following two aspects are important in our model where tacit knowledge creates incentives for R&D. First, since the creation of codified knowledge is highly uncertain, so is the generation of tacit knowledge. This is an ex ante uncertainty facing innovators. Second, when codified knowledge becomes obsolete, innovators may face obsolescence of the associated tacit knowledge. This is an ex post risk facing innovators. On the other hand, we also allows for a degree of transferability of tacit knowledge across codified knowledge to capture reality.[9]

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[7] The phrase is used in Zucker, Darby, and Brewer (1998).

[8] See below for a few studies which demonstrate a similar result.

[9] See Jovanovic and Nyarko (1996), for example.

The joint product hypothesis is related to but distinct from the concept of complementarity between technology and human capital in an important way. Technology-skill complementarity means that a given technology requires specific human capital to implement it. This insight has been widely used in the literature, e.g. to explain increasing wage inequality. In general, existing studies concern consequences of technology-skill complementarity. On the other hand, the joint product hypothesis is more relevant to the issue of how such complementarity may arise in the first place. In this sense, our study is closer to Acemoglu (1998). Moreover, a similar, but distinct hypothesis is used by Galor and Tsiddon (1997) and Jovanovic (1998) to represent knowledge-human capital complementarity.[10] They assume that schooling or/and on-the-job training boost human capital, and new knowledge is created as their byproducts. Given the absence of an explicit form of R&D, those studies are not suitable for the analysis of how R&D activity is compensated in a competitive economy. Our paper is also related to studies on multi-stage R&D. For example, Aghion and Howitt (1996) and Li (2000) develop models where a new variety of products must be created before their quality is improved. In Cozzi and Galli (2008), quality innovation requires two successes in R&D, capturing the notion that a novel scientific discovery necessitates further innovative activities for industrial applicability. In those models, two different types of research together generate codified knowledge, whereas one type of research produces two types of knowledge in our model.

The most important result of the present paper is that endogenous technical progress can be sustained in a competitive economy with constant returns to scale in rivalrous inputs, when codified and tacit knowledge are jointly produced in R&D. We also examine the issue of whether the competitive economy generates greater or smaller R&D incentives than a monopolistic economy. Analysis shows that results depend on the size of an economy. When it is large, the competitive economy grows faster than the monopolistic economy. The result is reversed when the size of the economy is small. This result has important implications regarding the role of intellectual property rights in promoting R&D.

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[10] There are three more approaches to model complementarity in the literature; (i) human capital accumulation is endogenous, but technology is exogenous (e.g. Caselli, 1999; Chari and Hopenhayn, 1991) and (ii) the reverse of the approach (i) (e.g. Lloyd-Ellis, 1999), (iii) technology and human capital are created endogenously in separate generation processes (e.g. Acemoglu, 1998).

There are some studies which offer different approaches to endogenize technical progress in a competitive economy. One strand of studies stress that codified knowledge is only imperfectly non-rival, arguing that the assumption of complete non-rivalry is an approximation of reality (Boldrin and Levine, 2008; Quah, 2002a,b).[11] By contrast, our model argues that tacit knowledge is imperfectly non-rival, maintaining an assumption that codified knowledge is perfectly non-rivalrous in line with existing R&D-based models. The second class of studies highlight the role of inframarginal rents that arise due to diminishing returns to scale (Shell, 1973; Hellwig and Irmen, 2001).[12] In our model, an assumption of constant returns to scale is maintained, so inframarginal rents play no role. On the other hand, in the model of Zeira (2006), industrialization raises workers' wages, which in turn induce firms to invent more capital-intensive machines, replacing workers. Through this process, an economy grows even without monopoly profits.

2 The Joint Product Hypothesis

2.1 Example 1

The current form of the biotechnology industry has been built on the remarkable discovery in 1973 of the basic technique for recombinant DNA by two academic scientists, Stanley Cohen and Herbert Boyer. The technique essentially allowed scientists to create an artificial DNA by taking a gene from an organism and inserting it to another. Codified knowledge of this technique is found in published journals. On the other hand, an important feature of the technology when it was invented is its complexity and tacitness required to implement it. That is, tacit knowledge of the technique was needed to implement codified knowledge in practice. This made the knowledge diffused only slowly, as other scientists learned through, e.g., coauthoring and Ph.D. supervision. Such slow diffusion of the technique reflects a slow diffusion process of tacit knowledge. It is tacit knowledge, since ideas of how to use the new codified

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[11] Wälde (2005) shows that innovation is sustained in a competitive market by assuming that innovators possess and sell the very first unit of new products, earning returns from R&D. This assumption makes knowledge imperfectly non-rival.

[12] On the other hand, Boldrin and Levine (2002a) considers a slightly different, but closely related issue of technology adoption in a competitive economy. See also Jovanovic and MacDonald (1994) who model technical innovation and imitation in a competitive industry in a partial equilibrium model.

knowledge is embodied in those who invented and learned the technique. For this reason, Zucker, Darby, and Brewer (1998) use "intellectual human capital" to refer to those who accumulate tacit knowledge. As more people learned the new technology, its tacitness fell. Zucker, Darby, and Brewer (1998) consider 1990 as the year when a gene sequence discovery became routinized. However, it does not mean that tacit knowledge became less useful. It simply means that the tacit knowledge was then embodied in a larger number of scientists than before.[13] In this sense, invention created new codified knowledge and, at the same time, tacit knowledge which was embodied in the inventors.[14]

2.2 Example 2

A diffusion process of tacit knowledge is also illustrated by the famous case of a hybrid corn. It was an invention of creating superior corn, which tripled corn grain yields in the U.S. between 1930s and 1980s.[15] But, "[i]t was not a single invention immediately adaptable everywhere" (Griliches, 1957, p. 502). Adaptable hybrids had to be created for different regions. Successful adaptation required an improved understanding of the technique and localities, resulting from efforts and experiments of farmers and entrepreneurs. That is, tacit knowledge of the technique was required for a successful adoption of the technique. This costly adoption process allowed seed developers not only to use the technology, but also to accumulate new tacit knowledge in the form of a deeper understanding of the technique.

2.3 Example 3

The above two examples concern a radical "invention of a method of inventing" (Griliches, 1957). The third example is the development of open source softwares. Developers at numerous institutions worldwide share the source code for some computer software programmes and contribute to their refinement by fixing bugs and modifying the code (e.g. Apache and Linux).[16] A license, attached to open source softwares, ensures their free distribution. Given their

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[13] Indeed, the fact that they still possess human capital did not change, even if knowledge diffusion had taken place instantaneously.

[14] See also Darby and Zucker (2003) for a similar example about nanotechnology.

[15] See Bauman and Crane (1992).

[16] Source code is what programmers write using one of programming language (e.g. C and Java), which can be modified by other programmers. Commercial softwares are created by converting a source code into machine language (a string of 0s and 1s), which is very difficult for humans to read or write.

non-rivalry and non-excludability, the open source software development came initially as a surprise to economists. What motivates developers to contribute? Two related answers are offered by Lerner and Tirole (2002).

First, participants in the development of open source softwares may be able to improve productivity of jobs set by the employer. One can also extend this argument to participants' overall productivity of programming jobs, which are not specific to the employer. By creating new codified knowledge (i.e. improving softwares), developers accumulate tacit knowledge, pointing to the case of the joint product hypothesis. The second reason suggested by Lerner and Tirole is career concerns. "[T]he compensation process is dynamic so that reputation-building – successfully submitting code that meets the rigorous standards of excellence demanded by the Open Source community – increases the individual's likelihood of accession to high-paying software employment" (Quah, 2002c, p. 29). According to this "signaling" view,[17] innovative activity increases returns from tacit knowledge.[18] Therefore, in the sense of market valuation, codified and tacit knowledge may be taken as joint products of R&D. Note that the two reasons offered by Lerner and Tirole suggest that an expected increase in returns, but not necessarily profits, induces people to engage in creative activities.

2.4 Empirical Evidence

The above discussion suggests that codified and tacit knowledge are created as joint products of creative activity. This joint product hypothesis is also consistent with a famous empirical study of Cohen and Levinthal (1989). They show that R&D has two faces; one is to create new knowledge and the second is to improve the firm's productivity to learn and absorb existing knowledge. The second face of R&D means that the quality of engineers and scientists, i.e. intellectual human capital, can be enhanced through R&D. Importantly, Cohen and Levinthal empirically confirm that firms recognize the second aspect of R&D in their decisions. They show the possibility that knowledge spillovers encourage R&D investment because of the absorptive nature of R&D, in contrast

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[17] This point is also relevant to science. Dasgupta and David (1987) hypothesize that financial remuneration for scientists is not trivial. Scientists build up reputation of their ability in their early career stages, and their research activity is financially compensated later. Indeed, this hypothesis is confirmed empirically by Stephan and Everhart (1998).

[18] Quoting an official who runs an IBM Linux development team, Financial Times (2003) writes that "Of the 1,000-odd developers actively working on Linux, more than half are now direct employees of big tech companies."

with a conventional view that the externality tends to create underinvestment in R&D. Their study shows that firms invest in R&D for dual purposes in anticipation of returns both from new knowledge and an enhanced absorptive capacity, which can be interpreted as the accumulation of tacit knowledge.[19]

2.5 Excludability of Tacit Knowledge

In the above examples tacit knowledge, once obtained, can be used for productive purposes. Viewed this way, returns from technology creation (and adoption) are interpreted to consist of two parts; the first part comes from the use of codified knowledge, and the second part from the accumulation of tacit knowledge. This indicates the possibility that new technology is created (and adopted) if returns from the accumulation of tacit knowledge alone is sufficient to compensate the cost of technology creation or/and adoption.

Codified knowledge is non-rivalrous, whereas tacit knowledge is rivalrous, since the person who possesses tacit knowledge cannot be physically present at two or more places simultaneously (see Romer, 1990). On the other hand, other people will eventually possess tacit knowledge via learning without degrading the quality of knowledge embodied in innovators and early adopters. In this sense, tacit knowledge also has an aspect of non-rivalry. Because of its non-rivalrous aspect, tacit knowledge diffuses to other people.

On the other hand, tacit knowledge is characterized by natural excludability (see Zucker, Darby, and Brewer, 1998). It is not particularly costly to prevent others from using the same knowledge at least initially because of high learning costs. This property makes a diffusion process of tacit knowledge (e.g. recombinant DNA) slow. For this reason, the original inventors and early adopters of the technique earn “excess” returns (see Stephan and Everhart, 1998).[20] Once diffusion completes, returns fall back to the “normal” level, as

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[19] In a more recent empirical study, Griffith, Redding, and Van Reenen (2004) confirm the importance of two “faces” of R&D in explaining productivity convergence among developed economies. On the theoretical front, absorptive capacity is modelled in Schumpeterian growth models of Keller (1996), Lloyd-Ellis (1999) and Griffith, Redding, and Van Reenen (2004).

[20] In biotechnology, the typical employment pattern of university-based scientists was that they affiliate with private firms, often retaining a faculty position. Stephan and Everhart (1998) find that 67.1% of scientists in their sample holds an equity position in the firm, and about 10% of the scientists hold sufficient options or stock which requires disclosure at an initial public offering. This kind of active involvement of academic scientists in the start-up and running of private firms “extends well beyond biotechnology,” according to (Jensen and Thursby, 2001, p. 242).

the supply of those with tacit knowledge increases. But as long as it is useful for productive purposes, tacit knowledge holders earn returns, which they could not have gained without innovative activity. The main argument of the current paper is that such competitive returns may be sufficient to motivate researchers to engage in R&D.[21]

3 Returns to Scale and Related Studies

Using the concept of returns to scale, this section relates our model to some of existing studies which demonstrate the possibility of endogenous technical progress in a competitive economy.

Consider the production function of output $Y = F(A, N, K)$ where A is the stock of codified knowledge which is non-rivalrous. K and N denote the number of workers with and without tacit knowledge. Assume that the production function exhibits constant returns to scale in rivalrous inputs N and K. In a competitive economy, income is exhausted as factor payments and there is no compensation for innovative activity, i.e.

$$Y = w^N N + w^K K \tag{1}$$

where $w^N = \frac{\partial F}{\partial N}$ and $w^K = \frac{\partial F}{\partial K}$. For this reason, Romer (1990) argues that imperfect competition is necessary for endogenous technical progress, so that profits compensate R&D activity.

In our model, on the other hand, imperfect competition and profits are not necessary for endogenous technical progress. This can be explained by rearranging (1) as

$$Y = w^N (N + K) + \left(w^K - w^N\right) K. \tag{2}$$

The first term on the right-hand side is payments to all rivalrous factors, N and K, before R&D generates tacit knowledge for K workers. This is the amount of payments, which must be made irrespective of whether or not technical progress occurs. After all, without technical progress all people in this economy would be identical without intellectual human capital. The second

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[21] The reward system of science described contrasts with a traditional view that profit motives play a minor role. This view is based on the assumption that scientific knowledge is non-rivalrous and non-excludable. This public good assumption may be less relevant to some scientific disciplines than before.

term represents total monetary rewards for those who created tacit knowledge through R&D. Given that codified and tacit knowledge are joint products of R&D, that term also represents compensation for R&D. In this sense, perfect competition is compatible with R&D activity.

Using equation (1), we next explain how our approach differs from existing studies. Here we consider two theoretical approaches to endogenize technical progress in a competitive economy. The first approach is to drop the assumption of constant returns to scale in rivalrous inputs, which results in the existence of quasi rents. In his partial equilibrium model, Shell (1973) suggests that such quasi rents can compensate innovative activity. Given that the logic of the usual replication argument, quasi rents are equivalent to payments to a fixed factor under constant returns to scale. Interpreting K as a fixed factor in (1), $w^K K$ represents such quasi rents. A downside of this argument is the lack of a clear link between the fixed factor and innovative activity, as pointed out by Romer (1990). In a modern incarnation of Shell's insight, Hellwig and Irmen (2001) develop a general-equilibrium model that attempts to correct this shortcoming.

The second approach is based on the observation that knowledge is only finitely expansible in practice. Finite expansibility essentially means that the quantity of a good can be reproduced at a finite rate (Quah, 2002a,b,c). Differently put, it means that knowledge diffuses at a finite rate. Under this assumption, the knowledge stock A is approximately rival. Given this, the production function $F(A, N, K)$ can be assumed to exhibit constant returns to scale in A, N and K. Under a special case of $Y = \beta A$, $\infty > \beta > 1$, Boldrin and Levine (2002b) show that the price of one piece of knowledge is positive. That is, innovative activity is compensated in a competitive economy. Quah (2002a) confirms Boldrin and Levine's result, but he shows that their result does not hold when time is continuous and knowledge is infinitely expansible.

4 Competitive Innovation

4.1 Consumers

To develop our argument in a familiar framework, we extend the quality-ladder model of Aghion and Howitt (1992). There are L number of workers who supply one unit of labour service at each point in time. They are identical ex ante, but heterogeneous in equilibrium due to the accumulation of tacit knowledge. Those who accumulate tacit knowledge are called "knowledge holders." We denote the number of knowledge holders by K, and others by N. All consumers are risk-neutral, hence the interest rate r is constant.

4.2 Production of Goods and Knowledge

Time is continuous. The production function of final output Y_t is

$$Y_t = A_t x_t^{\alpha}, \qquad 0 < \alpha < 1, \quad t = 0, 1, 2, \ldots. \tag{3}$$

x_t is the amount of intermediate goods, whose quality is given by A_t. A subscript t denotes the number of innovations, such that $A_{t+1} = \lambda A_t$ where $\lambda > 1$ measures the size of quality innovation. In this class of models, final output producers use the top-quality intermediate goods only (see below on this point).

Intermediate goods x_t are produced using the constant returns to scale technology in knowledge holders and non-holders. Using w_t^K and w_t^N to denote wage of *k*nowledge holders and *n*on-holders, respectively, define

$$c^x\left(w_t^K, w_t^N\right) \tag{4}$$

as a unit cost of x. An assumption implicit in (4) is that knowledge holders can be used across different quality levels due to transferability of tacit knowledge across different technologies. This point will be discussed in more detail in the next section.

The intermediate good industry is perfectly competitive. That is, a newly created blueprint of the state-of-the-art good is freely available. In this sense, codified knowledge is a pure public good. This assumption removes the possibility of monopoly profits being used to compensate R&D activity. Note that the price of an intermediate good equals the unit cost (4). It should be obvious, therefore, that final output producers always use the highest quality intermediate good available.

Using Shephard's lemma, demand for two type of workers are given by

$$K_t^x = c_K^x\left(w_t\right) x_t, \qquad \frac{\partial c_K^x\left(w_t\right)}{\partial w_t} < 0 \tag{5}$$

$$N_t^x = c_N^x\left(w_t\right) x_t, \qquad \frac{\partial c_N^x\left(w_t\right)}{\partial w_t} > 0 \tag{6}$$

where $w_t = \frac{w_t^K}{w_t^N}$ and $c_m^x \equiv \frac{\partial c^x}{\partial w_t^m}$, $m = K, N$.

The quality index of intermediate goods A_t rises by a factor $\lambda > 1$ whenever an innovation occurs through research activity. There is free entry in the R&D sector, i.e. any worker without tacit knowledge can engage in research if she wants. However, non-knowledge holders alone cannot produce new technology, and they have to work together with knowledge holders. One can imagine that tacit knowledge is passed on from knowledge holders like PhD students learning from their supervisors. Suppose that N_t^g number of workers without tacit knowledge engage in R&D. A typical worker j work with k_t^g number of knowledge holders to generate innovation with a Poisson arrival rate of

$$g_{jt} = f\left(k_t^g, 1\right), \qquad \frac{\partial f}{\partial k_t^g} > 0 \tag{7}$$

where $k_t^g \equiv \frac{K_t^g}{N_t^g}$ and K_t^g is the total number of knowledge holders employed in R&D in the economy as a whole. For simplicity, we assume that additional tacit knowledge is not obtained for those who already have one.

The economy-wide Poisson arrival rate of innovation in the intermediate goods industry is $g_t \equiv N_t^g g_{jt}$. We assume that the R&D technology (7) has the following property:

$$g_t = f\left(K_t^g, N_t^g\right). \tag{8}$$

(7) and (8) mean that the economy-wide R&D technology exhibits constant returns to scale in two types of workers. Given this, we use

$$c^g\left(w_t^K, w_t^N\right) \tag{9}$$

to denote a unit cost of g_t. Demand for knowledge holders and non-holders are given by

$$K_t^g = c_K^g\left(w_t\right) g_t, \qquad \frac{\partial c_K^g\left(w_t\right)}{\partial w_t} < 0 \tag{10}$$

$$N_t^g = c_N^g\left(w_t\right) g_t, \qquad \frac{\partial c_N^g\left(w_t\right)}{\partial w_t} > 0 \tag{11}$$

where $c_m^x \equiv \frac{\partial c^x}{\partial w_t^m}$, $m = K, N$.

4.3 Joint Products of R&D

The production of intermediate goods requires N_t^x and K_t^x. On the other hand, N_t^g and K_t^g are employed in the R&D sector. Therefore, the full-employment of workers requires

$$L = N_t^x + K_t^x + N_t^g + K_t^g. \tag{12}$$

All workers are identical ex ante, and the ex post heterogeneity of workers arises due to R&D activity. In the R&D sector, one of N_t^g workers (who work with knowledge holders) at most succeeds in R&D at each point in time. If successful, new knowledge in both codified and tacit forms is created. Codified knowledge comes as a blueprint of a higher quality good, and tacit knowledge as intellectual human capital. Those who fail in R&D cannot gain tacit knowledge.[22] These assumptions capture the joint product hypothesis in a simple way.

An important feature of technical progress is creative destruction in which new goods drive existing goods out of the market. Under the joint product hypothesis, it is plausible to assume that new knowledge, codified and tacit, renders obsolete not only existing codified knowledge, but also its associated tacit knowledge. On the other hand, we allow for the possibility that tacit knowledge is transferable across codified knowledge to some extent. For example, experiences and expertise associated with the invention of the state-of-the-art computer processor are likely to be useful for designing and producing the next-generation products, which render the former obsolete.[23] Put different, the creative destruction effect is likely to be smaller for tacit knowledge than for codified knowledge. This observation can be captured by assuming that each knowledge holder faces a risk of her tacit knowledge being obsolete with the probability of $1 \geq \mu > 0$ whenever innovation occurs. μ measures the degree of obsolescence of tacit knowledge or intellectual human capital due to technical progress.

Therefore, the number of those with tacit knowledge changes whenever innovation occurs, according to

$$K_{t+1}^x + K_{t+1}^g = 1 + (1-\mu)\left(K_t^x + K_t^g\right). \tag{13}$$

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[22] This assumption could be replaced with a more general assumption that only a fraction of unsuccessful workers gain tacit knowledge. But, this generality generates no additional insight.

[23] This observation is consistent with Nelson and Phelps (1966) who argue that, compared with unskilled workers, skilled workers have greater capacity to implement new technologies.

The left-hand side is the number of knowledge holders after innovation occurs. On the right-hand side is the sum of a worker who newly gains tacit knowledge and the number of knowledge holders whose tacit knowledge does not become obsolete.

Income mobility envisaged in equation (13) is summarized in Figure 1. Workers without tacit knowledge, if successful in R&D, join the pool of knowledge holders, boosting their income to w_t^K from w_t^N. On the other hand, a fraction μ of knowledge holders are driven down to the lower income class due to obsolescence of their tacit knowledge. This dynamic description suggests that social mobility is positively correlated with entrepreneurial activity, hence economic growth. This prediction seems consistent with data.[24]

4.4 R&D Incentives

Consider an R&D worker without tacit knowledge who earns a competitive wage w_t^N. If her innovative activity turns out to be fruitful, a blueprint is created for a higher quality intermediate good (codified knowledge), and at the same time, she will gain tacit knowledge. Given no profit being made, returns from R&D consist of an incremental competitive wage $w_t^K - w_t^N$ until her tacit knowledge becomes obsolete. Then, the expected present value of future flows of net incremental wages, V_t, is defined by

$$r_t V_{t+1} = w_{t+1}^K - w_{t+1}^N + g_{t+1}\left[(1-\mu)\left(V_{t+2} - V_{t+1}\right) - \mu V_{t+1}\right]. \qquad (14)$$

This equation is interpreted as follows. A worker who succeeds in R&D gains incremental wages $w_{t+1}^K - w_{t+1}^N$ until the next innovation arrives. When an additional innovation occurs, she loses the value V_{t+1} if her tacit knowledge becomes obsolete with the probability of μ or gains $V_{t+2} - V_{t+1}$ with the probability of $(1-\mu)$. Such gain and loss occurs with the Poisson arrival rate of g_{t+1}. Note that the innovator continues gaining returns from tacit knowledge with the probability of $(1-\mu)$. This represents the fact that an innovator partially "internalizes" what is known as the intertemporal knowledge spillover effect. Codified knowledge created by an innovator will be used by future researchers who do not pay for it. This positive externality is to some extent

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[24] See Quadrini (2000) on the link between entrepreneurship and social mobility, and Audretsch and Thurik (2001) and Reynolds, Camp, Bygrave, and Autio (2001) for a positive relationship between entrepreneurship and growth. Also see Galor and Tsiddon (1997) for a growth model where social mobility occurs.

mitigated due to transferrable tacit knowledge. That is, an innovator can capture future surplus by keeping tacit knowledge useful with a chance of $(1-\mu)$.[25]

There is free entry in R&D. Therefore, entry continues until excess returns from conducting R&D, which is given by

$$\Pi^g = V_{t+t} f\left(k_t^g, 1\right) - w_t^K k_t^g - w_t^N, \tag{15}$$

becomes zero. That is,[26]

$$V_{t+1} = c^g\left(w_t^K, w_t^N\right) \tag{16}$$

for $N_t^g > 0$. This condition also ensures that R&D workers without tacit knowledge are indifferent between working in the R&D and manufacturing sectors.

Free entry or (16) implies that part of $V_{t+1} f\left(k_t^g, 1\right)$ or "gross benefits" of R&D is used to pay wages to knowledge holders. In this sense, flows of incremental wages $w_t^K - w_t^N$ are "shared" between a non-knowledge holder and knowledge holders. However, wage payments are made only if R&D turns out successful. That is, knowledge holders do not get paid if R&D is unsuccessful. The reason why knowledge holders work in the R&D sector is that they receive a higher payment than w_t^K if R&D succeeds. Indeed, the expected payment that each knowledge holder receive is given by the left-hand side of the following equation:

$$V_{t+1} \frac{\partial f\left(k_t^g, 1\right)}{\partial k_t^g} = w_t^K, \tag{17}$$

which is the first-order condition for maximizing (15). Given that they are risk-neutral, knowledge holders engage in R&D as long as the expected payment is equivalent to wage that they can obtain for sure in the manufacturing sector.

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[25] In the model of Aghion and Howitt (1992), a similar feature arises in the case of incumbent firms conducting R&D. Also note that complete internalization requires $\mu = 0$, which cannot occur in our model.

[26] $\Pi^g = 0$ means $V_{t+1} f\left(K_t^g, N_t^g\right) = w_t^K K_t^g + w_t^N N_t^g$, using (8). This in turn implies (16), given (8) and (9).

4.5 Equilibrium Analysis

4.5.1 R&D Incentive Condition

In steady state, labor allocation between R&D and manufacturing must be time-invariant, i.e., K_t^m and N_t^m, $j = x, g$ must be constant. In such equilibrium, aggregate output Y_t grows at a rate of $(\lambda - 1)\, g$ on average,[27] and wages w_t^K and w_t^N grow at the same rate. Given this, one can easily confirm that

$$\frac{w_{t+1}^m}{w_t^m} = \lambda, \qquad m = K, N, \tag{18}$$

using the first order condition of profit maximization of intermediate goods producers.[28]

Using this result along with (14) and (16), we derive the following competitive R&D incentive condition:

$$\frac{(w-1)\,\lambda}{c^g\,(w)} = r + mg \tag{RI^C}$$

where

$$m \equiv \mu - (1-\mu)\,(\lambda - 1)\,. \tag{19}$$

This condition defines equilibrium R&D intensity g, taking relative factor prices as given. Alternatively, the condition shows an increase in factor payments, $w - 1$, required for tacit knowledge to incentivize workers to do R&D.

The competitive R&D incentive condition (RI^C) shows that relative wages w and R&D intensity g are positively related for $m > 0$ and negatively for $m < 0$. It is because of two opposing effects on the value of tacit knowledge V_t. First, tacit knowledge of a worker becomes obsolete with the probability of μ, reducing V to nil. Through this channel, a higher μ reduces the value of tacit knowledge, which in turn requires higher relative wages to generate enough incentives for R&D. This effect is captured by the first term of (19). Second, tacit knowledge is not rendered obsolete with the probability of $(1-\mu)$, generating capital gain $(\lambda - 1)$. Therefore, a higher μ tends to raise the value of tacit knowledge. Because of this channel, lower relative wages are enough to generate incentives for R&D. This effect is captured by the second term of (19). In what follows, we assume that the first effect dominates the

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[27] See Aghion and Howitt (1992) for details.

[28] The F.O.C is $\alpha A_t x_t^{\alpha-1} = c^x\left(w_t^K, w_t^N\right)$, using (3) and (4).

second effect, i.e., $m > 0$. This is because $m > 0$ means that higher competitive returns (i.e. higher relative wages) encourage R&D, and this case is most relevant to the analysis of the joint product hypothesis.[29]

4.5.2 Labor Market Condition

To determine equilibrium values of g and w, we close the model with the full employment condition of workers. In the long-run equilibrium, labor allocation across different sectors is constant. This means

$$\frac{1}{\mu} = K^x + K^g \tag{20}$$

from (13). This is effectively the resource constraint of knowledge holders. It says that their number is determined by a parameter μ which captures the degree of obsolescence of tacit knowledge. But, the allocation of knowledge holders between R&D and manufacturing is determined along with the R&D incentive condition (RI^C). Then, substituting (5) and (10) into the above condition yields

$$x = \frac{1/\mu - c_K^g(w)\, g}{c_K^x(w)} \equiv x(g, w), \quad x_g < 0, \quad x_w > 0 \tag{21}$$

where the numerator is assumed to be positive. The signs of the derivatives are easy to understand, interpreting (20) as the resource constraint of knowledge holders. A higher g mans the expansion of employment of those workers in R&D, which is possible only if employment in manufacturing falls, i.e. a reduction of x. On the other hand, higher relative wages reduces demand for knowledge holders in R&D, but increases it in the manufacturing sector. Since this expands the production of intermediate goods, x and w are positively related.

Using (6), (11), (20) and (21), rewrite (12) as

$$\begin{aligned} L - \frac{1}{\mu} &= c_N^x(w)\, x(g, w) + c_N^g(w)\, g \qquad (LM) \\ &= \frac{c_N^x(w)}{\mu c_K^x(w)} - c_N^x(w)\, \Psi(w)\, g \qquad (22) \end{aligned}$$

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[29] In the case of $m < 0$, higher competitive returns from R&D discourage R&D.

where

$$\Psi(w) \equiv \frac{c_K^g(w)}{c_K^x(w)} - \frac{c_N^g(w)}{c_N^x(w)}. \tag{23}$$

The labor market condition (LM) determines equilibrium relative wages, taking R&D intensity g as given. Its left-hand side is equivalent to the supply of workers without tacit knowledge, and its right-hand side shows demand for those workers in R&D and manufacturing. (LM) shows that its right-hand side is increasing in w. On the other hand, rearrangement gives (22), which increases or decreases in g, depending on $\Psi(w)$ or relative factor intensity in workers with and without tacit knowledge. $\Psi(w)$ is positive or negative if R&D is more or less intensive in knowledge holders than workers without tacit knowledge, respectively.

4.5.3 Long-run Equilibrium

To make exposition as clear as possible, we introduce two simplifications. First, we assume the absence of factor intensity reversal, i.e. $\Psi(w)$ does not change its sign. This allows us to remove one source of multiple equilibria. Instead, we consider two cases of $\Psi(w) > 0$ and $\Psi(w) < 0$, separately. Second, we focus upon a "normal" case which is consistent with a widely-accepted presumption that more patient nations (or economies with a low interest rate policy) grow faster. In fact, the majority of growth models predict that growth is higher with a lower subjective rate of time preference.[30] This prediction is intuitively clear, since more patient consumers use more resources to increase future consumption rather than the current consumption. Indeed, it seems difficult to make a case for impatient consumers devoting more resources to accelerate growth at the expense of the current consumption.

Given these simplifications, two relevant cases are depicted in Figure 2 and 3.[31] First, let us consider the case of $\Psi(w) > 0$, which is depicted in Figure 2. A positive slope of the labor market condition can be understood as follows. A higher R&D intensity g requires more workers in R&D. Since innovative activity is more intensive in knowledge holders than manufacturing, intensified R&D activity leads to higher relative wages.

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[30] On the other hand, there are some models which predict that growth accelerates as consumers become less patient (e.g. Dinopoulos and Thompson, 1998).

[31] A higher rate of time preference increases R&D intensity in the remaining unique-equilibrium case where the R&D incentive condition is steeper than the labor market condition in Figure 2. This case is not considered for the reason stated above.

To examine conditions for the existence of equilibrium, define w_{min}^{RI} and w_{min}^{LM} such that

$$\frac{\left(w_{min}^{RI}-1\right)\lambda}{c^{g}\left(w_{min}^{RI}\right)}=r, \qquad L-\frac{1}{\mu}=\frac{c_{N}^{x}\left(w_{min}^{LM}\right)}{\mu c_{K}^{x}\left(x_{min}^{LM}\right)}. \tag{24}$$

w_{min}^{RI} and w_{min}^{LM} are relative wages defined by the R&D incentive condition (RI^{C}) and the labor market condition (LM) when $g=0$. An interior equilibrium, as depicted in Figure 2, requires

$$w_{min}^{RI^{C}}<w_{min}^{LM}. \tag{25}$$

Another necessary condition comes from (21). Since x must be positive, equilibrium values of (g,w) must satisfy $g<1/\left(\mu c_{K}^{g}(w)\right)$. Given this, define

$$g_{max}=\frac{1}{\mu c_{K}^{g}\left(w_{max}\right)}. \tag{26}$$

This equation defines the demarcation curve between permissible and impermissible combinations of g and w for equilibrium in Figure 2. Substituting (26) into (RI^{C}) and (LM) yields

$$\frac{\left(w_{max}^{RI}-1\right)\lambda}{c^{g}\left(w_{max}^{RI}\right)}=r+\frac{m}{\mu c_{K}^{g}\left(w_{max}^{RI}\right)}, \qquad \mu\left(L-1\right)=\frac{c_{N}^{g}\left(w_{max}^{LM}\right)}{c_{K}^{g}\left(w_{max}^{LM}\right)}. \tag{27}$$

w_{max}^{RI} and w_{max}^{LM} are relative wages defined by the R&D incentive condition (RI^{C}) and the labor market condition (LM) along the demarcation curve (26). Given that the demarcation curve (26) is downward-sloping in (g,w) space, the following condition is necessary for the existence of equilibrium:

$$w_{max}^{RI^{C}}>w_{max}^{LM}. \tag{28}$$

The condition (28) is required for $x_t>0$ in equilibrium. Conditions (25) and (28) make sure that the two curves in Figure 2 intersect at least at one point in the interior of $w\in\left(w_{min}^{LM},w_{max}^{LM}\right)$.

Next, let us turn to the case of $\Psi(w)<0$, illustrated in Figure 3. A negative slope of the labor market condition is due to the assumption that R&D is now less intensive in knowledge holders than manufacturing. Note that (25) is again a necessary condition for an interior equilibrium. Therefore, the following proposition is clear from the discussion so far.

Proposition 1. *Under conditions* (25) *and* (28) *for* $\Psi(w) > 0$ *and* (25) *for* $\Psi(w) < 0$*, there exists equilibrium where technological progress occurs endogenously in an competitive economy when codified and tacit knowledge are produced as joint products of R&D.*

4.5.4 Comment on Relative Wages

The R&D incentive condition (RI^C) contains a hypothesis that relative factor prices are an important determinant of R&D. Some comments are in order on this point. First, studies on induced innovation (e.g. Kennedy, 1964) demonstrate that relative factor prices determine the direction of technical progress. On the other hand, the condition (RI^C) defines the overall rate of technical progress rather than its direction. A similar result is reported in Acemoglu (1998).

Second, w_{min}^{LM} is the minimum relative wages that are required to give enough incentives for workers to conduct R&D. If relative wages are lower than this threshold, no worker without tacit knowledge conduct R&D, and active R&D cannot be sustained in a competitive market. That is, a degree of wage inequality due to tacit knowledge must exist to drive innovation in a competitive economy. In addition, as far as the condition (RI^C) is concerned, there is a trade-off between wage inequality and R&D intensity.[32]

Third, the issue of increasing wage inequality in the U.S. in the 70s-80s is studied extensively in the literature (see Acemoglu, 2002), and a large number of studies attribute it to skill-biased technical progress. It basically means that technical advance increases relative demand for skilled workers.[33] That is, causation runs from skilled-biased technical progress to increasing wage inequality. On the other hand, Acemoglu (1998) argues that a higher wage inequality induces technical progress in a model where monopoly profits incentivize private agents to do R&D. In contrast, the present model demonstrates that the similar result can be obtained even without monopoly profits.

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[32] This statement is correct for $m > 0$, which is assumed in the present paper.

[33] See Leith, Li, and Garcia-Peñalosa (2003) for a study which examines the impact of technical progress on labor supply.

5 Introducing Monopoly Power

This section aims to answer the following questions. Dose a competitive market generate a larger or smaller incentive for innovative activity than a monopoly market? Under what conditions does technology advance at a faster rate under competition than monopoly? What is the impact of patent protection on R&D? To answer these questions, this section allows an innovator to earn monopoly profits due to codified knowledge in addition to returns from tacit knowledge.

5.1 Returns from Codified and Tacit Knowledge

An innovator is granted a patent for her product. The statutory duration of patent life is assumed to be infinite. However, to set a stage for policy analysis later, we assume that the government can determine the breadth of patents.[34] Suppose that A_t is the highest quality of intermediate goods. The patent breadth permits patent holders to prohibit the producer of the second-highest quality goods from producing quality above ϕA_{t-1} where $\lambda \geq \phi \geq 1$ measures the patent breadth.[35] The competitive economy analyzed above is equivalent to $\phi = \lambda$, i.e. no patent protection. Full patent protection is granted when $\phi = 1$.

Given the production function (3), demand for intermediate goods has a price elasticity of $-1/(1-\alpha)$. Therefore, taking into account that the second-highest quality producer sets its price at marginal cost, the top-quality firm charges the monopoly price of

$$p_t^x = \frac{c^x\left(w_t^K, w_t^N\right)}{\theta} \quad \text{where } \theta \equiv \begin{cases} \alpha & \text{for } \lambda \geq \alpha^{-\alpha}\phi \\ \left(\dfrac{\phi}{\lambda}\right)^{\frac{1}{\alpha}} & \text{for } \lambda < \alpha^{-\alpha}\phi \end{cases} \tag{29}$$

The case of $\theta \equiv \alpha$ is called "drastic innovation" in the sense that firms' price decisions are not constrained by potential competition from incumbent producers of lower-quality goods. This case arises if λ is sufficiently large. On the other hand, if λ is relatively small, the firm charges a limit price, i.e.

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[34] O'Donoghue, Scotchmer, and Thisse (1998) for more details regarding the breadth of patents.

[35] We are implicitly assuming that any quality level between A_t and A_{t-1} can be produced once A_t is invented.

$\theta \equiv \left(\frac{\phi}{\lambda}\right)^{\frac{1}{\alpha}}$. In this case, the top-quality firm charges the price such that final output producers are just indifferent between the state-of-the-art and second-highest quality products.

Given (29), we can derive profits that successful innovators earn:

$$\pi_t = \left(\frac{1}{\theta} - 1\right) c^x \left(w_t^K, w_t^N\right) x_t. \tag{30}$$

Note that $\pi_t = 0$ for $\phi = \lambda$, which is the case considered in the previous section.

Next let us calculate the expected value of future discounted returns from innovation. There are two types of returns from R&D, i.e. π_t and $w_t^K - w_t^N$. Therefore, the profit-augmented value of innovation, v_t, is defined by

$$rv_{t+1} = w_{t+1}^K - w_{t+1}^N + \pi_{t+1} + g_{t+1}[(1-\mu)\overbrace{(V_{t+2} - v_{t+1})}^{\Gamma_{t+2}} - \mu v_{t+1}] \tag{31a}$$

$$rV_{t+2} = w_{t+2}^K - w_{t+2}^N + g_{t+2}\left[(1-\mu)\left(V_{t+3} - V_{t+2}\right) - \mu V_{t+2}\right] \tag{31b}$$

π_{t+1} in (31a) represents returns from codified knowledge. This term tends to increase the value of innovation, ceteris paribus. We term this effect the *monopoly rent* effect, due to which R&D incentives tend to be higher than in the case of perfect competition. On the other hand, the terms inside the square brackets in (31a) show that the value of innovation changes due to an extra quality improvement for two reasons. First, the value v_{t+1} is lost with the probability of μ, if tacit knowledge becomes obsolete. Second, tacit knowledge remains useful with the probability of $(1-\mu)$, resulting in a change in the value of innovation Γ_{t+2}, which can be rewritten as

$$\Gamma_{t+2} = \lambda V_{t+1} - v_{t+1}. \tag{32}$$

This change can be decomposed into two parts. (i) The value changes from v_{t+1} to V_{t+1}, since profits are lost. This change is obviously negative, tending to make Γ_{t+2} negative, i.e. capital loss. (ii) Due to an extra innovation, the value increases by a factor λ. This effect tends to make Γ_{t+2} positive, leading to capital gain. If profits are sufficiently large, then the effect (i) dominates the effect (ii), hence, the value of Γ_{t+2} is negative. In this case, R&D incentives are adversely affected by the introduction of monopoly power. We call this the *capital loss* effect. Of course, it is possible that the effect (i) is dominated by the effect (ii), in which case Γ_{t+2} is positive and the capital loss effect has an opposite impact on R&D incentives.

The monopoly rent effect and the capital loss effect are identified above, taking relative wages are taken as given. In equilibrium, relative wages also change, affecting R&D incentives. Those three effects combined determined how R&D intensity changes due to monopoly power. The issue is explored in the next section.

5.2 Equilibrium Analysis

The R&D incentive condition is derived, making use of (16), (21), (30), (31a) and (31b):

$$\frac{(w-1)\lambda}{c^g(w)} = r + mg - \Delta(g, w; \theta) \tag{RI^M}$$

where

$$\Delta(g, w; \theta) \equiv \frac{\lambda c^x(w)\, x(g, w)}{c^g(w)} \left(\frac{1}{\theta} - 1\right)\left(1 - \frac{(1-\mu)\lambda g}{r + mg}\right), \tag{33a}$$

$$\frac{\partial \Delta(g, w; \theta)}{\partial g} < 0, \qquad \frac{\partial \Delta(g, w; \theta)}{\partial w} > 0, \qquad \frac{\partial \Delta(g, w; \theta)}{\partial \theta} < 0. \tag{33b}$$

$\Delta(g, w; \theta)$ is a new term due to the introduction of monopoly power. The term captures the monopoly rent effect and the capital loss effect. It is easy to see that $\Delta(g, w; \theta) = 0$ for $\theta = 1$ (i.e. $\phi = \lambda$). It says that the R&D incentive condition with monopoly (RI^M) collapses to (RI^C) in the absence of patent protection of codified knowledge.

To explore properties of $\Delta(g, w; \theta)$ further, note that $\Delta(g, w; \theta) > 0$ for $g = 0$. Therefore, given the first derivative in (33b), we can define the value of g such that

$$\Delta(\hat{g}, w; \theta) = 0 \quad \Rightarrow \quad 1 = \frac{(1-\mu)\lambda\hat{g}}{r + m\hat{g}} \text{ and } x(\hat{g}, w) > 0. \tag{34}$$

In words, (34) says that there exists the value of g that makes the Δ term disappear from the condition (RI^M). Note that $\hat{g}$ is unique. However, the existence of $\hat{g}$ depends on parameter values and specific forms of cost functions. In what follows, we focus on the case where $\hat{g}$ exists, since it gives us an interesting insight on the issue at hand.[36]

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[36] The following discussion will also briefly consider the case where $\hat{g}$ does not exist.

Now, we are in a position to compare competitive and monopoly equilibria. Remember that a sole difference between the R&D incentive conditions (RI^C) and (RI^M) is the term $\Delta(g, w; \theta)$, which captures the monopoly rent effect and the capital loss effect combined. In particular, those two effects cancel each other at $\hat{g}$ at which $\Delta(g, w; \theta) = 0$ when codified knowledge is protected by patents (i.e. $\phi < \lambda$). In other words, the R&D incentive conditions with and without monopoly power coincide at $\hat{g}$.

This property is exploited to draw Figure 4. In the figure, the monopoly R&D incentive condition (RI^M) is located above the competitive counterpart (RI^C) for $g < \hat{g}$, and the relative positions are reversed for $g > \hat{g}$. This can be easily checked by totally differentiating (RI^M) with respect to g and θ.[37] An intuition goes as follows. For $g > \hat{g}$, the capital loss effect dominates the monopoly rent effect, identified above. Therefore, g is higher for given relative wages in the monopoly equilibrium than in perfect competition. The reverse holds for $g < \hat{g}$.[38]

Turning to the labor market condition (LM), it is still valid in the presence of monopoly power. Taking advantage of this convenient feature, we identify two cases in Figure 4 where the two equilibrium conditions are depicted. In the first case, the total number of workers, L, is assumed to be relatively large. Both competitive and monopoly equilibria are located above $\hat{g}$. The figure shows that R&D intensity is lower in a monopoly economy. Intuitively, a large labor force means a large market for final output. Accordingly, profits are large, so that the capital loss effect dominates the monopoly rent effect. Note that the introduction of monopoly power decreases relative wages, reducing R&D incentives based on returns from tacit knowledge. Therefore, returns both from codified and tacit knowledge fall due to monopoly power.

In the second case, the working population is relatively small. Both competitive and monopoly equilibria are now located below $\hat{g}$. As Figure 4 confirms, R&D intensity is now higher in a monopoly economy. An intuitive explanation is the opposite of the above case. That is, a small market size generates low profits, hence the capital loss effect is also small or can even reinforce the monopoly rent effect, so that monopoly power boost R&D incentives. Note that relative wages increases due to monopoly power. Therefore,

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[37] We are assuming that $c^x(w)x(g, w)/c^g(w)$ increases in w. This is satisfied if the production functions of intermediate goods and R&D take Cobb-Douglas forms.

[38] For $g < \hat{g}$, the effect (i) of the capital loss effect, identified on page 22, can dominate the effect (ii). In this case, the capital loss effect reinforces the monopoly rent effect.

monopoly power raises returns both from codified and tacit knowledge.

Proposition 2. *Under* (34)*,*

1. *if L is relatively large, R&D intensity g is higher in a competitive economy than in an economy with monopoly power.*
2. *if L is relatively small, R&D intensity g is lower in a competitive economy than in an economy with monopoly power.*

There are two points that merit mention. First, if the condition (34) is not satisfied, $\hat{g}$ would be located in the infeasible (shaded) region in Figure 2 or 3. In this case, Result 2 of the above proposition only is relevant. That is, the introduction of monopoly power unambiguously promotes technical progress. Second, the point where the R&D incentive condition cuts the horizontal axis defines the minimum level of relative wages required for workers to do R&D. Figure 4 demonstrates that such minimum relative wages are lower in the monopoly equilibrium than the competitive equilibrium. This should be intuitive. Returns from tacit knowledge does not need to be too high because of additional returns from codified knowledge in the form of profits. In this sense, monopoly power somehow mitigates wage inequality required for technical progress.

5.3 Effect of Stronger Patent Protection

In our model, the breadth of patent is captured by a parameter ϕ. To examine its effect on R&D intensity, suppose initially $\phi = \lambda$ (i.e., $\theta = 1$), i.e. no monopoly profit. In this case, the monopoly R&D incentive condition coincides with the competitive counterpart, which is depicted as a thick curve. Starting from this situation, let us reduce ϕ marginally (stronger patent protection). Then, the monopoly firm charges the limit price in (29) (i.e. $\theta \equiv (\phi/\lambda)^{1/\alpha}$), earning profits

$$\pi_t = \left[\left(\frac{\lambda}{\phi}\right)^{\frac{1}{\alpha}} - 1\right] c^x\left(w_t^K, w_t^N\right) x_t. \tag{35}$$

Now, given that $\hat{g}$ is independent of ϕ, the monopoly R&D incentive condition pivots around a point E in Figure 4. If the initial equilibrium is located to the right of E, R&D intensity decreases. On the other hand, it increases if the initial equilibrium is located to the left of E. An intuition should be clear now. In the case of an equilibrium located to the right of point E in the figure, a large population means that monopoly profits are large. Therefore, the capital loss effect is so strong that a stronger patent protection reduces R&D incentives. The opposite intuition holds for the other case.[39]

Proposition 3. *Under* (34)*, a stronger patent protection of codified knowledge*

1. *reduces R&D intensity g and relative wages, if L is relatively large,*
2. *raises R&D intensity g and relative wages, if L is relatively small.*

As ϕ falls, the R&D incentive condition pivots clockwise around the point E in Figure 4. However, this movement applies as long as innovation is non-drastic, i.e., $\lambda < \alpha^{-\alpha}\phi$ in (29) is satisfied. If ϕ falls further, then innovation becomes drastic (i.e. the above inequality is violated) and the R&D incentive condition becomes independent of the parameter. In that case, a strong patent protection cannot alter R&D intensity. That is, there is a limit on the effect of strengthening patent protection.

6 Conclusion

R&D-based models of endogenous technical progress rest on a premise that technical progress is driven by profit-seeking entrepreneurs. This literature led to a dominant view that endogenous technical advance is not consistent with perfect competition with constant returns to scale. Departing from this dominant perspective, this paper demonstrates that technical progress endogenously occurs in a perfectly competitive economy under constant returns to scale in rivalrous inputs. The result is based on a hypothesis that two types of knowledge, codified and tacit, are joint products of innovative activity.

In the paper, a simple model is developed to capture the hypothesis. Returns that successful innovators earn consist of returns from the creation of tacit knowledge and monopoly profits, if codified knowledge is excludable. In a competitive economy, R&D is compensated by competitive returns from tacit knowledge alone.

An additional insight of the present study concerns the effect of monopoly power of a creator of codified knowledge. We demonstrate that monopoly power does not necessarily increase R&D intensity. The case is identified

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[39] Bessen and Maskin (2000) also show that strengthening patent protection can discourage innovation.

where R&D intensity falls with the introduction of monopoly power. This means that a stronger patent protection, which a government may adopt to promote innovation, can harm R&D incentives against its original intention. We believe that these findings are important in furthering the understanding of the nature of technical progress and patent policy.

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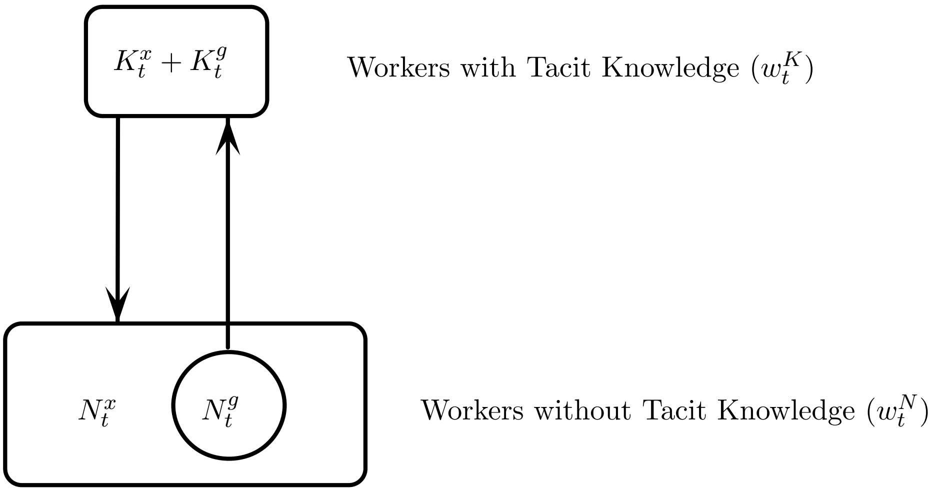

Figure 1: Flows of workers.

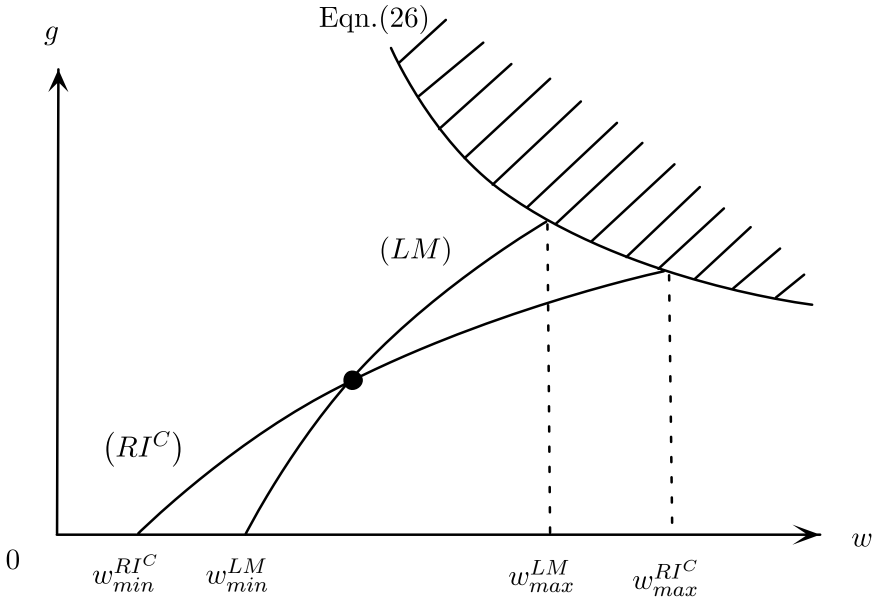

Figure 2: Competitive equilibrium for $\Psi(w) > 0$.

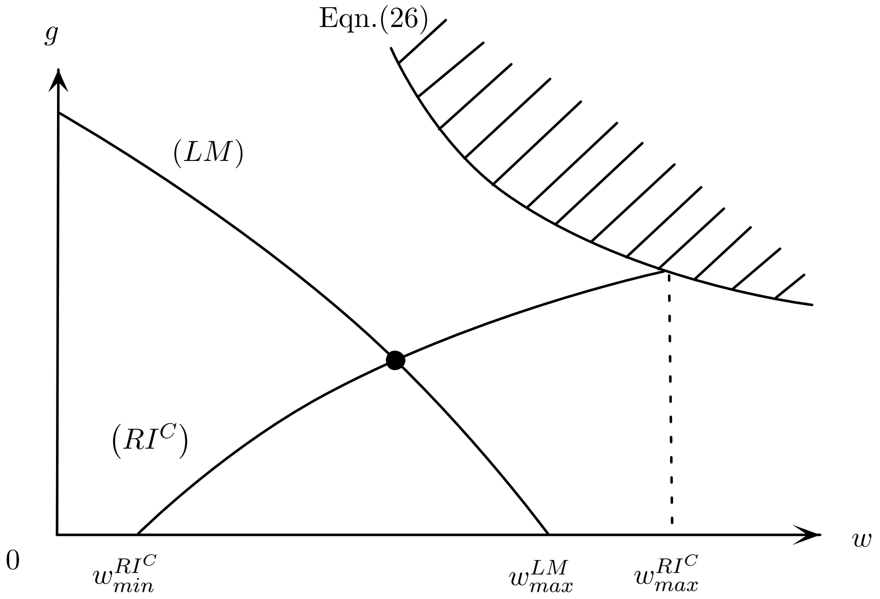

Figure 3: Competitive equilibrium for $\Psi(w) < 0$.

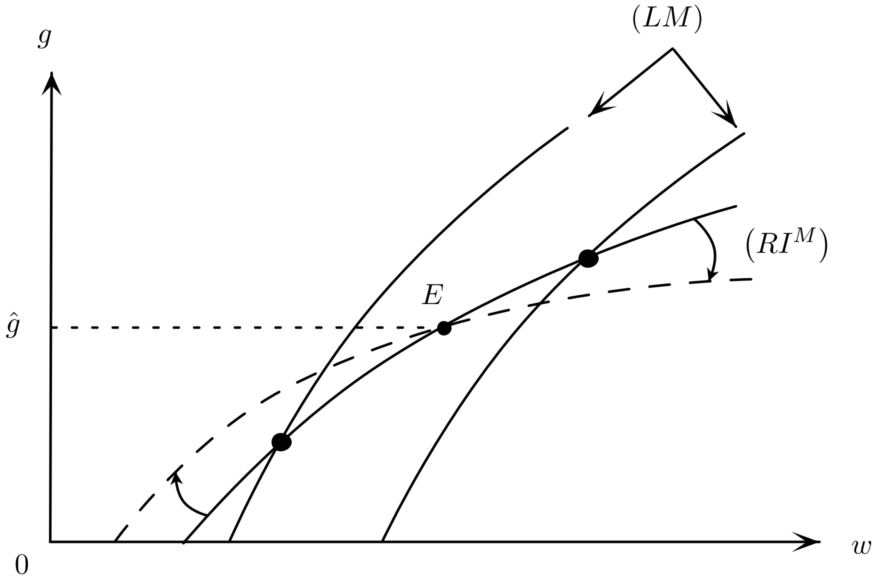

Figure 4: The effect of monopoly power.