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REGULAR ARTICLE

The division of labor in innovation between general purpose technology and special purpose technology

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Abstract This paper constructs an endogenous growth model that identifies three patterns in the division of labor in terms of innovation between GPT and SPT sectors: (1) the SPT stage, (2) the GPT-SPT joint-research stage, and (3) the autonomous GPT stage. It is shown that the emergence of GPT only has a temporary level effect, and a negative effect on economic growth. However, the new phenomenon of the autonomous GPT stage has a positive influence on both growth and level effects. This result theoretically explains the emergence and resolution of the IT productivity paradox.

Keywords General purpose technology · Special purpose technology · Division of labor in innovation · Economic growth

JEL Classification O14 · O33

1 Introduction

The purpose of this paper is to establish an endogenous economic model that involves innovation in the two sectors of general purpose technology and special purpose technology, and to examine the economic implications of different patterns of interaction between the two technologies. General purpose

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technology (GPT henceforth), as typified by machine tools, semiconductors, IT, etc., refers to fundamental technology that is utilized in diverse industries. In contrast, special purpose technology (SPT) is technology that is utilized only in specific areas and industries, where both SPT and GPT are utilized in order to produce final goods. Needless to say, the two technologies exist in a complementary relationship, since the SPT level rises if the level of GPT is high.

The importance of GPT has been pointed out by Rosenberg (1976) in his pioneering study on the machine-tool industry. He argued that the GPT sector is extremely important for economic development because GPT plays a central role in the diffusion of technology, and thus has a major influence on innovation.[1]

However, it has been only relatively recently that this proposition has been studied in a formal manner. The partial equilibrium model of Bresnahan and Trajtenberg (1995) was a pioneering work; thereafter, there have been several examples of research that postulated GPT as a driver of endogenous economic growth, such as Helpman and Trajtenberg (1994, 1996, 1998) (HT model henceforth). These models are impressive achievements that formalized the role of GPT; for example, the incorporation of GPT has made it possible to provide an integrated explanation on the relationship between economic growth and business fluctuations. However, in the HT model and subsequent papers extending the HT model, innovation in GPT is assumed to be no more than an exogenous shock, while only innovation in the special purpose technology sector (the SPT sector) is seen as endogenous.

This paper attempts to endogenize both the GPT and SPT sectors and to create a dynamic general equilibrium model that examines the economic implications of different institutional arrangements regarding interaction between the GPT and SPT sectors. Obviously, the economic implications of interaction between GPT and SPT cannot be fully examined without endogenizing innovation processes in both sectors. We distinguish three patterns in the division of labor in innovation between the GPT and SPT sectors—(1) the SPT stage, (2) the GPT-SPT joint-research stage, and (3) the autonomous GPT stage—and analyze the characteristics of the market equilibrium for each stage of innovation activities and elucidate their economic implications.

In this analysis, it is shown that the emergence of GPT, as long as it takes the form of joint-research with the SPT sector, only has a temporary level effect, and a negative effect on economic growth when compared with the previous stage. This result is consistent with the IT productivity paradox, in which IT diffusion fails to contribute to economic growth. In addition, the new phenomenon of the autonomous GPT stage has a positive influence on both growth and level effects. This result theoretically supports the empirical studies

[1] Rosenberg (1976) specifically points out the importance of the capital-goods sector, and that basically corresponds to the GPT sector referred to in this study.

showing that the IT productivity paradox was resolved in the U.S. economy in the 1990s.[2] Thus the model provides a theoretical explanation for both the emergence of the IT paradox and its recent resolution.

The rest of the paper is organized as follows. The next section reviews major studies on GPT, clarifying the differences between models in the early studies and the model proposed here. Sections 3–5 provide detailed explanations of the model: Section 3 explains the model of the SPT stage, Section 4 the model of the GPT-SPT joint-research stage, and Section 5 the autonomous GPT stage. Section 6 compares social welfare and market equilibrium and discusses socially desirable technology policies. Finally, Section 7 concludes the discussion.

2 Review of previous studies

Although there has recently been a growing interest in GPT in the economic profession, little work has been done on formalizing the idea.[3] Bresnahan and Trajtenberg (1995) first proposed the concept of GPT, and developed a model for the conditions of the "dynamic game" between the GPT sector and the SPT sector. However, in that model, only these two sectors exist, while the kinds of influence exerted by the interaction between the sectors on social welfare and consumer behavior are not clarified.

The growth effects of GPT in a general equilibrium framework were formally analyzed by Helpman and Trajtenberg (1994, 1996, 1998). In their models, GPT requires complementary inputs before they can be applied in the production process. Complementary inputs developed for previous GPT are not utilized for a newly arrived GPT. As a result, the sequential arrival of GPTs generates business cycles. Following the HT model, most of the subsequent work on GPT focused attention on the cyclical properties caused by the arrival of GPT. Aghion and Howitt (1998) partially endogenized the arrival times of successive GPTs by adding a second stage of component-building to the innovation process in a basic Schumpeterian model of endogenous growth and attempted to extend the model so as to make it consistent with empirical observations. Petsas (2003) analyzed the dynamic effects of GPT within a scale-invariant Schumpeterian growth model and showed that transitional growth cycles exist even if population growth is introduced. Eriksson and Lindh (2000) modified the HT model by allowing for positive technological externalities in the process of component innovation and only partial replacement of old components with a newly arrival of GPT.

Following these previous studies, this paper adopts the framework of a basic Schumpeterian growth model and explores the economic implications of GPT.

[2] For example, refer to Brynjolfsson and Hitt (1996).

[3] See Helpman (1998) for a summary of previous research on GPT.

However, the model in this paper differs greatly from those in previous studies in the following respects. First, this paper focuses attention on the growth implications of institutional arrangements regarding patterns of interaction between the GPT and SPT sectors, rather than focusing on growth cycles. This model does not generate growth cycles, since innovations in the GPT and SPT sectors are allowed to proceed simultaneously. Although the growth cycle is an interesting phenomenon, different patterns of interaction between the GPT and SPT sectors also deserve equal attention, as a historical analysis of the US machine tool industry by Rosenberg (1976) persuasively demonstrates. The kind of influence exerted by these institutional factors on the economic growth rate and R&D has become a central topic in innovation research, but one that has not yet been formally analyzed.

As noted above, we distinguish three patterns in the division of labor in innovation between the GPT and SPT sectors: (1) the SPT stage, (2) the GPT-SPT joint-research stage, and (3) the autonomous GPT stage. The SPT stage implies that no GPT sectors emerge in the economy so that each SPT sector internally develops production technology. In contrast, the GPT-SPT joint-research stage allows SPT firms to jointly develop production technology with GPT firms. The outcome of this joint research is available to all other SPT sectors, except SPT firms within the same SPT sector. Otherwise, the SPT firm cannot recoup the profits from innovation. Finally, at the autonomous GPT stage, innovation is executed by GPT sectors alone without the help of SPT firms.

Here we attempt to analyze the characteristics of the market equilibrium for each stage of innovation activities and elucidate their economic implications. Thus, this paper, while derived from the quality ladder model, goes one step beyond previous related research by encompassing endogenous innovation in the GPT sector, and the division of labor in innovation between the GPT and SPT sectors.

Second, a major difference is that our model incorporates R&D and innovation in both the GPT and SPT sectors, while previous growth cycle models have described innovation only in one sector. More precisely, previous studies such as Aghion and Howitt (1998) assumed that the arrival of a new GPT followed some stochastic process (a Poisson process), but moments of this stochastic process were exogenously fixed.

In contrast, this paper endogenizes this arrival time by making the arrival rate depend on research intensity, as assumed in a standard one-sector Schumpeterian growth model.[4] Thus the arrival times of both GPT and SPT are influenced by the division of labor in innovation between the two sectors.

[4]There are several papers that combine vertical and horizontal innovations and endogenize both innovation processes (Young 1998; Dinopoulos and Thompson 1998; Peretto 1998; Howitt 1999). The difference between these studies and this paper is that the latter endogenizes two-tier vertical innovations in order to focus on the role of GPT.

3 The model

This section describes the basic framework of the model, and then describes the economic growth model at the SPT stage.

3.1 Household

Consider a continuous-time closed economy, assuming that a representative household maximizes the utility function

$$U(t) = \int_t^{\infty} e^{-\rho(s-t)} u(s)\, ds, \tag{1}$$

where $\rho > 0$ denotes the rate of time preference rate, and $u(s)$ is the instantaneous utility function, which is specified as follows:

$$u = \ln c,$$
$$c = \exp\left(\int_0^N \ln\left[\sum_j y_{ij}\right] di\right), \qquad N \geq 1, \tag{2}$$

where c denotes the consumption level and y_{ij} indicates final goods supplied by the jth generation of production technology developed in the ith SPT sector. As is clear from (2), the size of the SPT sectors is expressed as N and the household purchases final goods from each SPT sector.

The household maximizes (1) subject to the intertemporal budget constraint

$$\int_t^{\infty} e^{-[R(\tau)-R(t)]} c(\tau)\, d\tau \leq B(t) + \int_t^{\infty} e^{-[R(\tau)-R(t)]} w(\tau)\, d\tau,$$

$$R(\tau) = \int_0^{\tau} r(s)\, ds,$$

where $w(t)$ denotes wage income, $B(t)$ denotes the household's stock of assets at time t, $R(t)$ represents the discount factor from time zero to t, and $r(t)$ indicates the instantaneous discount factor at time t.

The first-order conditions of the household's optimization require that

$$\frac{\dot{c}(t)}{c(t)} = r(t) - \rho, \tag{3}$$

and the transversality condition holds

$$\lim_{s\to\infty} e^{-R(s)} B(s) = 0.$$

In this model, the price of c (the sum of all final goods) is normalized at 1, and the amount of expenditure by the household is equivalent to c. Thus, the demand for the final goods is given by

$$y_i = \frac{c}{Np_i}. \tag{4}$$

3.2 The SPT sector

Assume that each SPT sector produces final goods by the following production function:

$$y_i = e^{\lambda j} l_i, \tag{5}$$

where $e^{\lambda j}\,(j \geq 1)$ indicates the j generation's production technology for the final goods, and productivity increases with each succeeding generation.

As is clear from the production function, no SPT firms purchase technology from outside the firm. At this stage, since the GPT sector has yet to appear, the technology used in each sector is limited to internally developed technology. Therefore, the model at this stage is essentially the same as the existing quality ladder model. The marginal costs in the SPT sector are given by

$$MC = e^{-\lambda j} w.$$

Hence, the limit price charged by the jth new quality leader becomes

$$p_i = e^{(1-j)\lambda} w. \tag{6}$$

As is clear from (2), the representative household purchases final goods only from an SPT firm that has successfully developed the state-of-the-art technology. As a result, the jth quality leader will be replaced as soon as a winner of the R&D race for the $j+1$th appears.

The instantaneous profits of the quality leader is, according to (4) and (6), is given by

$$\pi_S = \frac{\left(1 - e^{-\lambda}\right) c}{N}. \tag{7}$$

3.3 R&D activities

In the SPT sector, a firm that has already succeeded in developing the newest generation of technology produces final goods, while other firms conduct their R&D aimed at innovation in the next generation. Following previous studies of the quality ladder model, let us assume that this R&D follows the Poisson process such that the instantaneous probability of an entrepreneurial success is provided by ι_s. For simplicity, assume that the amount of labor ι_s must be allocated to innovation activities to achieve the instantaneous probability ι_s without loss of generality.[5]

The stock value at time t of a quality leader is equal to the present discounted value of its profit stream subsequent to t, which is given by

$$v(t) = \int_t^{\infty} e^{-(R(\tau)-R(t))} e^{-\iota_S(\tau-t)} \pi_S d\tau,$$

where it is assumed that firms in each SPT sector exist up to [0, 1], and because of the symmetry of the model, the amount invested in R&D by each firm is at the same level. As a result, the probability that a quality leader will not be replaced from time t to time τ is given by $e^{-\iota_S(\tau-t)}$. Therefore, this term is multiplied on the right side of the above equation. Differentiating that equation with respect to t, we get the following non-arbitrage condition:

$$rv = \dot{v} + \frac{\left(1 - e^{-\lambda}\right) c}{N} - \iota_S v. \tag{8}$$

This value of v represents the economic value of innovation, while, in order to achieve the instantaneous probability of innovation ι_s, the same amount of labor, ι_s must be allocated to innovation activities. Since there are no entry barriers to this R&D race, the net value of innovation turns out to be zero in equilibrium, i.e., $\iota_S v \le \iota_S w$. Needless to say, $\iota_s > 0$ is satisfied whenever this condition holds with equality. Thus, the free entry condition is given by

$$v \le w. \tag{9}$$

Finally, assuming the total amount of labor is L, we obtain the labor market clearing condition

$$\int_0^N l_i di + N\iota_S = L. \tag{10}$$

This completes the model of the SPT stage. Note that, since this specification follows a standard Schumpeterian growth model, the results in what follows suffer from the scale effects that have been criticized by Jones (1995a, b). In addition, a constant population size of L is not a realistic assumption. In the Appendix, we will present a modified model with positive population growth that removes these scale effects. However, this modified model in no way changes the qualitative results below, so we maintain the assumptions of constant population size and constant returns in R&D technology to avoid unnecessary complications.

[5] In order to assure $\iota_s \le 1$ is satisfied, it might be better to assume $\eta\iota_s$ labor must be allocated to achieve the instantaneous probability of ι_s where $\eta > 1$. However, this additional assumption does not change the results in the paper at all, so we assume $\eta = 1$ in what follows for simplicity.

By solving (3), (7), (8), (9), and (10), we obtain the following result:

Lemma 1 *The market equilibrium at the SPT stage is given as follows:*

The amount of R&D investment: $\iota_0 = e^{-\lambda}\left\{\left(e^{\lambda}-1\right)\frac{L}{N}-\rho\right\}$
The growth rate: $g_0 = \lambda e^{-\lambda}\left\{\left(e^{\lambda}-1\right)L - N\rho\right\}$,
where $\frac{(e^{\lambda}-1)L}{N} > \rho$.

4 GPT-SPT joint-research stage

In the model of the SPT stage described above, innovation is carried out only by SPT firms. However, the advanced economies are characterized by the emergence of GPT sectors that provide technology to many SPT sectors, as suggested by Rosenberg (1976). This section analyzes the emergence of GPT sectors that develop technology in joint cooperation with SPT firms where significant learning takes place in the interaction between SPT and GPT sectors. With technological spillovers of GPT to other SPT sectors, GPT sectors play an important role in economic development and growth, according to Rosenberg (1976). This section attempts to formalize the emergence of GPT sectors in the economy and examine its economic implications.

4.1 SPT sector

The main difference between the SPT stage and the GPT-SPT joint-research stage lies in the type of R&D that the SPT and GPT sectors carry out. In the joint-research stage, R&D is conducted jointly by GPT and SPT firms. When the joint research succeeds, the GPT firm can provide the new technology to other SPT sectors. However, it is assumed that no technology is provided to direct rivals of its SPT partner.[6]

While SPT firms do not gain profits through providing the new jointly developed technology to other SPT firms, they can enjoy a monopoly position within their own sector. This monopoly lasts until a rival SPT firm succeeds in developing the latest generation of technology in joint research with another GPT firm. Accordingly, as long as the new technology is not provided to a rival firm in the same sector, the incentive exists to engage in R&D jointly with a GPT firm.

[6]If the supply of new technology to rival firms were to be allowed, there would be no incentive for the SPT firm to engage in joint-research. This is because, once the technology is supplied to a rival firm, positive profit could no longer be secured. Of course, if this condition were to be loosened, with new technology being sold to rival firms in the same sector, and with the SPT firm being able to secure the profit, then there would be an incentive for joint R&D. However, to simplify the analysis, it is assumed in this paper that no new technology is supplied to rival firms in the same sector.

This sort of joint R&D between the GPT and SPT sectors reflects the role, pointed out by Rosenberg (1976), that the U.S. machine-tool industry played as a transmission center of innovation. Rosenberg argued that the learning process in the economy was facilitated in two steps: (1) new skills and techniques were developed or perfected in response to the demands of specific customers; and (2) once they were acquired, the machine tool industry was the main transmission center for the transfer of new skills and techniques to the entire machine-using sector of the economy. This type of learning process implies that GPT firms and specific SPT firms jointly engaged in research in order to resolve specific technical problems, and the new technology produced thereby was then provided to other firms by the GPT firm. Consequently, the aforementioned hypothesis of the GPT-SPT joint-research stage reflects the role of the GPT sector as a transmission center of innovation.

From this perspective, the production function of each SPT sector can be specified as

$$y_i = e^{\int_0^N j_m dm \lambda} l_i \equiv A_1 l_i. \tag{11}$$

The difference between (5) and (11) is that, in the latter, new technology developed by all other SPT sectors is purchased from GPT firms, and all SPT firms use identical production technology. In other words, the new technology that is developed jointly by an SPT firm with a GPT firm is provided to all SPT firms in other SPT sectors. For this reason, compared with the SPT stage, the shift to this joint-research stage causes an improvement in the production technology level used by SPT firms. However, in the long term, it is not necessarily obvious whether this effect becomes significant or not. We will discuss this issue in a later section.

With this production function, the marginal costs and limit price are given by

$$MC = A_1^{-1} w,$$
$$p_i = e^{\lambda} A_1^{-1} w.$$

The instantaneous profit of a quality leader is now specified as

$$\pi_S = \frac{\left(1 - e^{-\lambda}\right) c}{N}.$$

Note that this instantaneous profit is equal to the one in the model of the SPT stage, since all SPT firms are assumed to improve their productivity to the same level here. With the utility function of this model, the elasticity of substitution is unity, implying that as long as there is symmetry in the improvement of productivity, no change will occur in the profit.

4.2 GPT sector

Next, assume the size of GPT sectors that emerge at this stage to be unity, instead of N, which is smaller than that of SPT sectors. This assumption is consistent with the previous arguments on GPT sectors by Rosenberg (1976), where the US machine tool industry, for example, supplies its products to diverse industries including textiles, railroads, arms, sewing machines, bicycles and automobiles. In other words, industrialization was characterized by the introduction of a relatively small number of broadly similar productive processes to a large number of industries.

For simplicity, it is assumed that the marginal costs of newly developed technology are zero for GPT firms that conduct successful joint research. If the newly developed technology takes the form of intellectual assets, such as patents or software, this assumption would be plausible. Obviously, it is also possible to construct a model with positive marginal costs, but it makes the model unnecessarily complicated without providing many insights.

With zero marginal costs, the limit price of GPT makes no sense. This is because in terms of costs, there is no disparity with rival firms. Given this situation, it is assumed here that SPT firms always prefer to introduce new, state-of-the-art technology, as long as the GPT price does not exceed the profits gained by the SPT firm. This assumption is reasonable since if a SPT firm adopts less efficient GPT, the rival firms would instead purchase the latest technology and dominate the whole market. As a result, SPT firms always have an incentive to adopt only the latest GPTs.

Thus, the upper limit of the GPT price is set at the profit level of the SPT firm, and its lower limit set at zero. The eventual price level ends up being set somewhere between those two limits, according to the respective bargaining power of the GPT and SPT firms. At this joint-research stage, the level at which the price eventually settles at is determined endogenously through market equilibrium.

The non-arbitrage condition for the GPT firm, according to a similar argument as above, can be expressed as follows:

$$rv = \dot{v} + \frac{\left(1 - e^{-\lambda}\right) c}{N} - Np_g - \left(\iota_a + \iota_g\right) v,$$

$$rv = \dot{v} + Np_g - \left(\iota_a + \iota_g\right) v,$$

where p_g refers to the GPT price.

Since free-entry conditions for joint R&D activities are assumed here, the expected value of the innovation in the GPT and SPT sectors ends up being the same. If the two were not at the same level, R&D resources would be invested only in projects with higher expected value. Hence, if R&D is carried out by both the GPT and SPT sectors, the expected value of innovation ends up settling at the same level, v.

The free-entry condition for R&D activity and the labor market clearing condition are, respectively,

$$v \leq w,$$

$$\int_0^N l_i di + N\iota_S + N\iota_g = L.$$

This completes the model of the joint-research stage. and the following results can be derived:

Lemma 2 *The market-equilibrium at the GPT-SPT joint-research stage is given as follows:*

The amount of R&D Investment: $\iota_1 \equiv \iota_S + \iota_g = \frac{1}{e^{\lambda}+1}\left\{\left(e^{\lambda}-1\right)\frac{L}{N}-2\rho\right\}$,
The growth rate: $g_1 = \frac{N\lambda}{e^{\lambda}+1}\left\{\left(e^{\lambda}-1\right)L-2N\rho\right\}$,
where $\frac{\left(e^{\lambda}-1\right)L}{2N} > \rho$.

From this lemma, we see that $\frac{\partial\iota_1}{\partial N} < 0$ is satisfied. In other words, an increase in the size of the SPT sectors will cause a proportional decline in R&D investment. However, the economic growth rate is not proportionate to N, but rather to N^2. This is due to the effect of the GPT sector as a transmission center of innovation, making it necessary to pay attention to the fact that an increase in N does not necessarily lead to a decline in the economic growth rate.

4.3 Comparison of the SPT stage with the joint-research stage

Now compare the growth rates and economic levels of the SPT stage and the GPT-SPT joint-research stage. First, a comparison of growth rates yields

$$g_1 - g_0 \propto \left(N - e^{-\lambda} - 1\right)\left[\left(e^{\lambda}-1\right)L - N\rho\right] - N^2\rho \quad (\equiv \Delta g_{10}).$$

This difference in growth rates can be either positive or negative, depending on the size of L, λ, ρ and N. For example, take the case of $N = 1$. In this situation, we get

$$\Delta g_{10} = -\left(1 - e^{-\lambda}\right)(L + \rho) < 0.$$

In this case, the growth rate of the joint-research stage is smaller than that of the SPT stage, no matter how big L, ρ and λ are. Now define the following:

$$N^* \equiv \frac{1}{4}\left\{\frac{\left(e^{\lambda}-1\right)L}{\rho} + e^{-\lambda} + 1\right\}.$$

It follows that Δg_{10} represents an increasing function of N when $N^* > N$, and a decreasing function when $N^* < N$.

According to Lemma 2, the upper limit of N is given by

$$\bar{N} \equiv \frac{\left(e^{\lambda}-1\right)L}{2\rho}.$$

In this case, we get

$$\Delta g_{10} = -\left(e^{-\lambda}+1\right)\frac{\left(e^{\lambda}-1\right)L}{2} < 0.$$

Accordingly, the shift to the joint-research stage can result in a negative growth effect at the lower and upper limits of N.[7] Δg_{10} is at its largest at N^*, but whether the value in that case is positive or negative depends on the size of L, λ and ρ. At least it can be stated here that, although the growth effect improves slightly as N increases, once it crosses the N^* threshold and approaches the maximum, it once again becomes negative.

Meanwhile, the level effect turns positive when the shift is made to the joint-research stage. This result is clear from (5) and (11) as well. Since the production function of SPT firm increases significantly, the economic level also rises. However, since the growth effect is negative if N stays at a low level or if it approaches its upper limit, the long-term level effect will also be negative. Consequently, when the shift is made to the joint-research stage, the economic level may improve, but in the long run, its level effect attenuates, implying that a higher economic level could be achieved by remaining in the SPT stage. A summary of the above discussion results in the following proposition:

Proposition 1 *When the level of N is near either its upper or lower limit, the emergence of GPT through joint research causes a decline in the growth rate compared with the SPT stage. For this reason, the economic level increases temporarily right after the shift, but its level effect turns negative in the long run.*

This proposition suggests that, when N is either small or near its upper limit, the economic effect of the emergence of GPT, which Rosenberg (1976) regards as positive, is actually only a temporary shock, and in the long term, both the level effect and the growth effect decline. Of course, it is dangerous to interpret the results of the model and apply them directly to reality. However, it should be noted that this theoretical result stands in sharp contrast to the previous studies by Rosenberg (1976). That is, the emergence of the GPT sector does not increase the economic growth rate, but instead may decrease it.

This result, which seemingly goes against common sense, must be understood within the general equilibrium framework. Put differently, the division of labor between the GPT and SPT sectors through joint research has the advantage of temporarily giving each SPT firm a significant technological boost. However, the amount of production expands as well, owing to the

[7] The term "growth effect" used here refers to the difference in growth rates between two stages at issue. The term "level effect" is used with the similar meaning.

increase in productivity, leading to a reduction in prices. In this model, the price elasticity of demand is unity, thus offsetting the increase in production by the decrease in price. Moreover, the shift to the joint-research stage increases the total costs of production technology, consisting of all state-of-the-art GPTs available in the economy. As a result, wages decrease, and the value function of innovation v also declines. For this reason, the incentive for innovation declines as well. However, since the economic growth rate is N^2 times the amount of R&D investment, whether or not the growth rate declines in the end depends on the value of N.

Usually, in the initial stages of the emergence of the GPT sector, N is not predicted to have a large value. The availability of GPT expands as time progresses. Thus, according to Proposition 1, in the initial periods, it follows that the growth rate is negative in comparison to the SPT stage, and as N goes on increasing, the growth effect is improved. The increase in N can be accounted for from the perspective of time adjustment process, as pointed out by David (1990). That is, it takes significant time for GPT to diffuse in an economy, so that the number of SPT sectors adopting GPTs (i.e., N) increases only slowly.

However, if N expands beyond N^*, the growth effect once again starts to decline, and finally turns negative. In that case, the long-term level effect may also turn out to be negative. Consequently, it is clear that the emergence of the GPT sector, as long as it takes the form of joint research, does not necessarily generate a desirable effect in the long run, depending on the size of N. This may be one reason why the diffusion of GPT does not necessarily contribute to productivity growth, as is the case with the IT productivity paradox.

5 Autonomous GPT stage

The aforementioned analysis illustrates the negative influence of the emergence of the GPT sectors, one that shares similarities with the IT productivity paradox, which implies that the diffusion of IT has not contributed to an increase in productivity. The emergence of the GPT sectors has given the economy a temporary boost, increasing the stock of GPT. Meanwhile, given the fact that the economic growth rate has decreased, the increase in the stock of GPT does not lead to productivity growth. As a consequence, while GPT has diffused, causing the level of the economy to rise, there is no statistical evidence of its positive effect on productivity, which can be called "technology paradox".

However, as N increases, the economic growth rate recovers, leading to the possibility of a positive growth effect. Yet, if N expands beyond a certain level, it will lead conversely to a negative growth effect. A long-term continuation of the IT productivity paradox could be explained as follows: the initial phase will witness a low level of N, spike rapidly and then reach its upper limit.

At the same time, though, empirical studies in the 1990s and later, such as Brynjolfsson and Hitt (1996), demonstrated the resolution of the IT productivity paradox in many instances. If the findings of such studies are reliable, then it cannot be interpreted as simply an expansion of N. Rather, another sort of mechanism must be at work yielding a different result from that above.

5.1 SPT sector and GPT sector

Regarding the resolution of IT productivity paradox, this paper attempts to construct a model of the new phase of the economy as the autonomous GPT stage, exploring the characteristics of its equilibrium. The autonomous GPT stage refers to a situation in which new technologies are no longer developed in cooperation with the SPT sector, but rather one in which both the GPT and SPT sectors engage in their own R&D separately, so as to produce innovations.

The production function of the SPT sector in those circumstances can be formulated as follows:

$$y_i = e^{h_i^S \lambda_S + \int_0^1 j_m^g dm \lambda_g} l_i \equiv A_2 e^{h_i^S \lambda_S} l_i, \tag{12}$$

where $h_i^S \geq 1$ refers to the latest generation of technology in the ith SPT sector. For the autonomous GPT stage to have any significance, the condition

$$\lambda_g \geq N\lambda,$$

must be fulfilled. Otherwise, the autonomous GPT stage would lead to a decline in the production technology of each SPT firm, and there would be no incentive in the first place to shift to the new stage.[8]

Each SPT firm purchases the latest GPT from the GPT sector [0,1]. Additionally, the SPT sector carries out its own innovations. In this case, even when the shift to the autonomous GPT stage takes place, it is assumed that the technological framework used in the joint research stage (between the SPT and GPT sectors) remains available to SPT firms, and

$$\lambda_S \geq \lambda,$$

is guaranteed.

By definition, SPT is not available to a wide range of customers, and it is assumed that it cannot be provided to other SPT firms. Accordingly, the technology developed by other SPT firms is not reflected in this production function.

Given this production function, the marginal costs (MC) and limit price imposed by the SPT (p_i) are as follows:

$$MC = A_2^{-1} e^{-h_i^S \lambda_S} w$$

$$p_i = A_2^{-1} e^{(1-h_i^S)\lambda_S} w.$$

[8]This paper does not specifically model the shift between stages that occurs endogenously. However, one can postulate, for example, that each SPT firm always attempts to improve the level of production technology. Otherwise, the rival firms dominate the market instead. Thus, a shift will not take place without at least a temporary level effect.

Thereafter, a model can be constructed in a similar manner to the preceding sections. First, the non-arbitrage condition is set as follows:

$$rv = \dot{v} + \frac{\left(1 - e^{-\lambda_S}\right) c}{N} - p_g - \iota_S v, \tag{13}$$

$$rv = \dot{v} + Np_g - \iota_g v.$$

However, the difference with the joint-research stage can be found in that the price p_g which the GPT sector imposes on the SPT sector is no longer endogenously determined, as described in the previous section, but the GPT firm can determine the price, according to the extent of its bargaining power. For the time being, the price is assumed to be set at a fixed ratio of the wages. Specifically, the following equation is assumed:

$$\beta \equiv p_g / w.$$

If no specific restrictions are placed on the bargaining position of the GPT firm, the most reasonable level of β would be the limit price for the SPT firm.[9] In other words, the GPT price would be set at the same amount as the profit of the SPT firm. In that case, however, the equality of (13) is no longer satisfied, and R&D in the SPT sector would not be carried out. Put differently, if the GPT firm sets the limit price, innovations would only take place in the GPT sector.

Such a phenomenon is not unrealistic at all. For instance, in the area of personal computers, innovations are implemented by only a handful of GPT firms, and the bulk of the profits are concentrated there. As the independence of GPT in terms of innovation progresses, the limit price set by the GPT firm is expected to come to the fore. Thus, the following analysis focuses on this particular case of the limit price.

Then, the free-entry condition and labor market clearing condition are, respectively,

$$v \leq w,$$

$$\int_0^N l_i di + N\iota_S + \iota_g = L.$$

These conditions lead to the following lemma:

Lemma 3 *The market equilibrium at the autonomous GPT stage is as follows:*

The amount of R&D investment (SPT sector): $\iota_S = \left(1 - e^{-\lambda_S}\right) \frac{L}{N} - e^{-\lambda_S} \left(1 + \frac{1-e^{\lambda_S}}{N}\right) \rho - \beta$,

The amount of R&D investment (GPT Sector): $\iota_g = N\beta - \rho$,

[9] Here, for convenience, the term "limit price" is also used for prices set at the same level of the SPT firm's profit.

The growth: rate: $g_2 = \lambda_S \left\{\left(1 - e^{-\lambda_S}\right) L - e^{-\lambda_S} \left(N + 1 - e^{\lambda_S}\right) \rho - N\beta\right\} + \lambda_g N \left(N\beta - \rho\right).$

5.2 Comparison of joint-research stage and GPT autonomy stage

A comparison of the market equilibrium in the autonomous GPT stage and that in the joint-research stage is set out below. To obtain a clear result, a specific examination of the limit price case will be made. However, the result is not limited to this case alone, but is also applicable to instances when the GPT firm has a relatively high level of bargaining power.

First compare the growth rate in the two stages. When the GPT firm sets the limit price, the GPT price is given by

$$p_g = \frac{\left(1 - e^{-\lambda_S}\right) c}{N},$$

and (13) is no longer satisfied. Consequently, $\iota_S = 0$, and the growth rate in such a case is as follows:

$$g_2 = \lambda_g N \left[\left(1 - e^{-\lambda_S}\right) L - e^{-\lambda_S} \rho\right].$$

This growth rate is different from that of the joint-research stage in that the former is monotonically increasing in N.

From Lemma 2, we obtain

$$-g_1 = \lambda_g N \left[\left(1 - e^{-\lambda_S}\right) L - e^{-\lambda_S} \rho\right] - \frac{\lambda N}{e^{\lambda} + 1} \left\{\left(e^{\lambda} - 1\right) L - 2N\rho\right\} \quad (\equiv \Delta_{21}).$$

The magnitude of the growth rate difference in this case varies depending on the size of λ_g, λ_S, λ and N. If λ is small and λ_g, λ_S and N are large enough (for instance, $\lambda_g = N_\lambda$, $\lambda_S = \lambda$), then $\Delta_{21} > 0$ is obtained so that the growth effect is observed in the shift to the autonomous GPT stage. Since $\lambda_g \geq N\lambda$ and $\lambda_S \geq \lambda$ are assumed above, $\Delta_{21} > 0$ turns out to be guaranteed here.

This result is intuitive. If λ_g and λ_S are both large, then the growth rate will increase as a matter of course. This situation will occur even if no innovation is implemented in the SPT sector. The reason is that, if λ_S is large, the limit price imposed by the GPT firm grows larger, leading to an increase in the amount of R&D investment by the GPT firm.

In addition, in the joint-research stage, the new technology developed by the SPT sector, which has the size of N, must all be purchased, whereas in the autonomous GPT stage, the new technology can be purchased from GPT sectors, which has the size of 1, leading to a reduction in the cost of production technology. This cost-reduction effect becomes ever more prominent as N increases.

Meanwhile, a comparison of the level effect leads to the following:

$$\ln c_2 - \ln c_1 \propto \ln \frac{(L + \rho)\left(e^{\lambda} + 1\right)}{2\left(L + N\rho\right)} + \ln A_2 - \ln A_1 + \lambda_a (h - 1),$$

where $h \geq 1$ refers to the average SPT level in the initial stages. Since we know from Lemma 2 that

$$\frac{\left(e^{\lambda}-1\right)L}{2N} > \rho,$$

the first item on the right side of the equation is:

$$\ln\frac{(L+\rho)\left(e^{\lambda}+1\right)}{2\left(L+N\rho\right)} > \ln\frac{(L+\rho)}{L} > 0.$$

Also, since (11), (12) and the growth effect are all positive, $\ln A_2 \geq \ln A_1$ will always be true. This confirms that the level effect will also be positive as a consequence.

Here also, λ_g and λ_S have a positive influence on the level effect, while N has a negative effect on the initial level. However, because an increase in N will heighten the growth effect, in the long run it will cause the level effect to increase. Consequently, we arrive at the following proposition:

Proposition 2 *The transition from the GPT-SPT joint-research stage to the autonomous GPT stage produces a positive growth effect and level effect.*

6 Social welfare and technology policies

This section will compare the market equilibrium and Pareto-optimal solutions for the different economies in the three stages explored above, so as to derive policy implications.

6.1 SPT stage

First, let us seek the socially optimal solution for the SPT stage. Social welfare is expressed as a utility function of a representative household. The social planner's problem is to maximize the utility function by determining the amount of workers to be allocated to production and R&D. Consequently, this problem can be formulated as follows:

$$\max_{X,\iota} U = \int_{t}^{\infty} e^{-\rho(s-t)} N \left[\ln X(\tau) - \ln N + \lambda I(\tau)\right] d\tau,$$

$$s.t. \quad \dot{I}(\tau) = \iota, \ \ N\iota + X = L.$$

The Hamiltonian is then given by

$$H = \ln X(\tau) - \ln N + \lambda I(\tau) + \theta\left(\frac{L-X}{N}\right).$$

Solving this problem, we obtain

$$\iota_0^* = \frac{L}{N} - \frac{\rho}{\lambda}.$$

From the results of Lemma 1, a comparison of the amount of R&D investment is as follows:

$$\iota_0^* - \iota_0 \propto \frac{L}{\rho N} + 1 - \frac{e^{\lambda}}{\lambda}.$$

Clearly, the right hand side of this expression is positive when λ is small, and negative when its value crosses a certain threshold. Consequently, the following proposition can be derived:

Proposition 3 *In the SPT stage, a large value for λ leads to excessive investment, and a small value to insufficient investment.*

This is basically the same result arrived at in previous research, such as Grossman and Helpman (1991). Their model differs from the one described above in showing that a small λ value also resulted in excessive investment.[10] However, the result remains the same here insofar as a large λ value leads to excessive investment. As this SPT stage is basically the same as traditional endogenous economic growth models, this result is not surprising.

6.2 GPT-SPT joint-research stage

Next, the socially optimal value for the GPT-SPT joint-research stage can be sought in the same way as above. In this case, the optimization problem is as follows:

$$\max_{X,\iota} U = \int_t^{\infty} e^{-\rho(s-t)} N \left[\ln X(\tau) - \ln N + \lambda I N(\tau)\right] d\tau,$$

$$s.t. \quad \dot{I}(\tau) = \iota, \;\; N\iota + X = L.$$

Solving this equation leads to the following:

$$\iota_1^* = \frac{L}{N} - \frac{\rho}{N\lambda}.$$

From Lemma 2, we obtain

$$\iota_1^* - \iota_1 \propto 2\left(\frac{L}{\rho} + N\right) - \frac{e^{\lambda} + 1}{\lambda}.$$

On the right side of this expression, any value of λ greater than 1.278 makes it a decreasing function of λ; a sufficiently large λ will thus make the right side negative. In contrast, when λ is less than 1.278, it becomes an increasing function. As for the latter case, the sign of the right side is dependent on the

[10] This difference derives from the difference in the specifications related to product quality. In contrast to Grossman and Helpman (1991), where λ^j is specified, this paper uses , producing a trivial difference. However, the basic result remains the same.

values for L, ρ and N, so it may not necessarily turn negative. However, in the former case, a sufficiently large λ will always result in the sign of the right side becoming negative. Accordingly, the following proposition is obtained:

Proposition 4 *In the GPT-SPT joint-research stage, excessive investment will occur when λ is sufficiently large, or when it is sufficiently small (and L and N are also small). When λ falls in an intermediate range between those two poles (and L and N are large), there will be insufficient investment.*

6.3 GPT autonomy stage

One of the results described above—that excessive investment takes place when λ is large—is consistent with previous research. However, as far as the autonomous GPT stage is concerned, the model presented above differs greatly from the existing endogenous growth model in that it incorporates a distinct division of labor in innovation. This raises the possibility that the socially optimal solution will also differ from the existing one.

In the autonomous GPT stage, the social planner's problem is formulated as follows:

$$\max_{X,\iota_S,\iota_g} U = \int_t^{\infty} e^{-\rho(s-t)} N \left[\lambda_S I_S(\tau) + \lambda_g I_g(\tau) + \ln X - \ln N\right] d\tau,$$

$$s.t. \quad \dot{I}_S(\tau) = \iota_S, \quad \dot{I}_g(\tau) = \iota_g, \;\; \iota_g + N\iota_S + X = L.$$

In this utility function, R&D stocks in GPT and SPT are in a linear relationship. Consequently, from the social planner's perspective, it is more efficient not to make investments equally in GPT and SPT, but rather to concentrate investments in the type of technology that has the larger value of λ.

In this case, let us assume that $\lambda_g > \lambda_S$ is satisfied. Given this situation, the socially optimal solution is therefore:

$$\iota^* = L - \frac{\rho}{\lambda_g}.$$

In the case of the autonomous GPT stage, in market equilibrium, both GPT and SPT sectors will invest in R&D unless GPT firms set the limit price. In contrast, the socially optimal solution shows that R&D investment will occur only in the GPT sector. However, as stated above, the reasonable assumption here is limit price so that both the market equilibrium and socially optimal solution make the same predictions about the innovation pattern.

The problem is the relative size of the respective amounts invested in R&D by the GPT sector. Lemma 3 shows that the amount invested in R&D, when GPT firms set a limit price, is as follows:

$$\iota_2 = \left(1 - e^{-\lambda_S}\right) L - e^{-\lambda_S}\rho.$$

Thus, we obtain

$$\iota^* - \iota_g \propto L + \rho - \frac{\rho e^{\lambda_S}}{\lambda_g}.$$

The right side of the expression is an increasing function of λ_g, and a decreasing function of λ_S. This leads to the following proposition:

Proposition 5 *The autonomous GPT stage gives rise to insufficient investment when λ_g is sufficiently large, and excessive investment when it is small. When λ_S is sufficiently large, it leads to excessive investment, and to insufficient investment when small.*

In this way, λ_g and λ_S generate contrasting results. Whereas the latter is similar to that of the SPT stage and the GPT-SPT joint-research stage, the former is completely the opposite. Consequently, the direction of technology policies once the autonomous GPT stage is reached is completely different from the direction prevailing at other stages. These results lead to the following corollary:

Corollary *In the SPT stage and GPT-SPT joint-research stage, a large value of λ produces excessive investment, so it is socially desirable to tax R&D investment. In contrast, at the autonomous GPT stage, a large value of λ_g leads to insufficient investment, making it desirable to provide subsidies to R&D in the GPT sector. When the value of λ_S is large, however, excessive investment prevails, making taxation more desirable.*

Thus, the optimal direction for technology policy differs according to the manner in which labor is divided between the GPT and SPT sectors in terms of innovation. Particularly, during the autonomous GPT stage, it becomes desirable to promote R&D in the GPT sector as much as possible, so if the limit price is not set, it will become necessary to restrain R&D in the SPT sector. This result has not been pointed out in the related literature on endogenous growth.

7 Concluding remarks

This paper constructed an endogenous growth model, analyzing the economic effect of the pattern of the division of labor between the GPT and SPT sectors in terms of innovation. What it revealed is that, in a majority of cases, the emergence of GPT, as long as it takes the form of joint-research with the SPT sector, only has a temporary level effect, and a negative effect on economic growth when compared with the previous stage. This highlights the negative aspects of the GPT sector as a transmission center of innovation.

In addition, the new phenomenon of the autonomous GPT stage has a positive influence on both growth and level effects. This result theoretically supports the empirical studies showing that the IT productivity paradox was resolved for the U.S. economy in the 1990s. To put it differently, the IT industry in the United States witnessed the development of the autonomous GPT sectors, with an expansion of N and an increase in the size of each step of the quality ladder, thereby resulting in improvements of both growth and level effects, thus resolving the IT productivity paradox.

The results of this paper make it clear that it is possible to explain the emergence and resolution of the IT productivity paradox, not merely through the IT productivity paradox as time-consuming adjustment process (David 1990), but also through a shift in division of labor in innovation between the GPT sector and the SPT sector.

Also, the results of this paper reveal that the direction of optimal technology policies is profoundly different between the SPT stage and GPT-SPT joint-research stage, on the one hand, and the autonomous GPT stage, on the other. In the first two stages, a larger size of each step of the quality ladder results in excessive investment, requiring taxation in order to restrain investment in R&D. In contrast, in the latter stage, investment will be insufficient if the GPT sector has larger steps of the quality ladder, making it necessary to provide subsidies to or reduce taxes on the GPT sector so as to promote R&D investments in the GPT sector while restraining those in the SPT sector. To the best of our knowledge, little attention has been paid to these kinds of policy implications in the previous studies.

Appendix

All of the above analysis in this paper assumes that the size of population, L, remains constant, so that the growth rate depends positively upon L. Thus, as population growth causes the size of the economy to increase over time, R&D resources also grow, leading to a higher growth rate. Although this assumption greatly simplifies the analysis, it may call its empirical relevance into question. As Jones (1995a, b) suggested with time series evidence, these scale effects are not observed with positive population growth. In this appendix, we will present the model with positive population growth, while removing scale effects.

Although several mechanisms that remove scale effects have been proposed by several papers, dealing with topics such as R&D cost function increasing in scale (Segerstrom 1998), product proliferation effects (Young 1998; Howitt 1999; Dinopoulos and Thompson 1998), and the crowding-in effect (Peretto 1998), among others, we will adopt the assumption of the R&D cost function increasing in scale, since this assumption does not change the basic structure of the above model, and, moreover, it is more consistent with empirical observations, as discussed in Segerstrom (1998).

In the above model, the instantaneous probability of innovation ι_s is achieved by the same amount of labor, ι_s allocated to innovation activities. But now it is assumed that $\iota_s X$ must be allocated to innovation activities. X measures the difficulty of innovation and is specified as

$$X = h^{-1} L, \tag{14}$$

where $h > 0$ is satisfied. That is, the difficulty of innovation increases as the population gets larger. The size of population is assumed to grow exponentially, such that

$$\frac{\dot{L}}{L} = g_l > 0.$$

With these modified assumptions, let us recalculate the equilibrium R&D investment and growth rate in the three stages. First, consider the SPT stage. The assumption of R&D difficulty changes the free entry condition as

$$v = wX. \tag{15}$$

Assuming $w = 1$, we can derive from this condition

$$\frac{\dot{v}}{v} = \frac{\dot{X}}{X} = g_{l.}$$

Substituting this and (15) into (8) gives

$$r = g_l + \frac{(h - N_{l_S})(e^{\lambda} - 1)}{N} - l_S. \tag{16}$$

Solving this, we obtain

$$\iota_0 = e^{-\lambda} \left\{ \left(e^{\lambda} - 1\right) \frac{h}{N} - (\rho - g_l) \right\},$$
$$g_0 = \lambda e^{-\lambda} \left\{ \left(e^{\lambda} - 1\right) h - N (\rho - g_l) \right\}.$$

Although this model removes scale effects, compared with lemma 1, there exist only minor differences between this and lemma 1. The only differences are that h appears instead of L, and ρ is corrected by $\rho - g_l$ in this model. As this holds true in the other stages, and the procedure to derive equilibrium remains the same, we omit the rest of the model without scale effects. Instead, we summarize the results of all three stages in the next lemma.

The market equilibrium without scale effects are given as follows:

i) The SPT Stage

$$\iota_0 = e^{-\lambda} \left\{ \left(e^{\lambda} - 1\right) \frac{h}{N} - (\rho - g_l) \right\},$$
$$g_0 = \lambda e^{-\lambda} \left\{ \left(e^{\lambda} - 1\right) h - N (\rho - g_l) \right\}.$$

ii) The GPT-SPT Joint-research Stage

$$\iota_1 \equiv \iota_S + \iota_g = \frac{1}{e^\lambda + 1}\left\{\left(e^\lambda - 1\right)\frac{h}{N} - -2\left(\rho - g_l\right)\right\},$$

$$g_1 = \frac{N\lambda}{e^\lambda + 1}\left\{\left(e^\lambda - 1\right)h - 2N\left(\rho - g_l\right)\right\}.$$

iii) The GPT Autonomy Stage

$$\iota_S = \left(1 - e^{-\lambda_S}\right)\frac{h}{N} - e^{-\lambda_S}\left(1 + \frac{1 - e^{\lambda_S}}{N}\right)\left(\rho - g_l\right) - \frac{\beta}{X},$$

$$\iota_g = \frac{N\beta}{X} - \left(\rho - g_l\right),$$

$$g_2 = \lambda_S\left\{\left(1 - e^{-\lambda_S}\right)h - e^{-\lambda_S}\left(N + 1 - e^{\lambda_S}\right)\left(\rho - g_l\right) - \frac{N\beta}{X}\right\}$$
$$+\lambda_g N\left\{\frac{N\beta}{X} - \left(\rho - g_l\right)\right\}.$$

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