Technological Competition, Cumulative Innovation, and Technological Development Schemes

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Technological Competition, Cumulative Innovation, and Technological Development Schemes *

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Abstract

This study investigates which technological development schemes are most desirable for technological competition and cumulative innovation, including follow-on innovation, under uncertainty conditions. Technological competition is likely to generate a social overincentive for innovations; it does so for follow-on innovation, especially when the consumer surplus is negligible. This study determines that a contract with a grant-back clause combined with an appropriate profit distribution mitigates social overinvestment in both initial and follow-on innovation; and therefore, improves social welfare. Moreover, this study demonstrates that if a government can specify a particular profit distribution between firms, the socially optimal investment in initial innovation can be realized. Conversely, assuming a significantly positive consumer surplus instead, this study reveals that competition in follow-on innovation creates a higher level of social welfare.

KEYWORDS: technological competition, cumulative innovation, technological development scheme, grant-back clause
JEL CLASSIFICATION: L24; O32; O34

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1 Introduction

In the real world, firms constantly undertake research and development (R&D) to acquire a competitive advantage by differentiating their products or lowering their costs. Moreover, innovations generated by R&D can enhance social welfare. Many studies have thus far focused on whether the R&D incentives of firms are socially optimal: they are often too high or too low. Specifically, technological appropriability – the degree to which an innovator exclusively retains the returns to R&D – influences the incentive to innovate.

Arrow (1962) argued that technologies cannot be appropriated in nature and that due to this non-appropriability characteristics, firms may invest less in R&D than they normally would at the socially optimal level. Nevertheless, we must not forget the fact that technologies can sometimes be appropriated using a patent system, which effectively ensures technological appropriability for a long time (Nordhaus, 1969). When firms can appropriate their innovations through patent protections, a social overinvestment in R&D may arise. Access to an exclusionary patent right by only one innovator means that subsequent innovators may infringe upon the patent right of the first innovator, even if they have established successful innovations based on the first. This gives rise to a "patent race," similar to a rank-order tournament, in which firms tend to invest in R&D beyond a socially optimal level with the intention of being the first innovator. Consequently, R&D investments by firms other than the winner might be considered socially wasteful (Barzel, 1968).

Examining cumulative innovation, in which improvements build on previous advances in the stream of innovation, complicates this picture. Scotchmer (1991, 2004) and Green and Scotchmer (1995) illustrated that both initial and follow-on innovators' incentives to innovate should be considered under cumulative innovation. As these authors emphasized, if the externalities of creating further improvements in cumulative innovation are not fully internalized, the initial innovator may not have a sufficient incentive to diffuse his or her original innovation. On this point, licensing practices can strengthen the social incentive to innovate by providing an initial innovator with an exclusionary patent right that can be traded with follow-on innovators.

In particular, "grant-back clauses," which are a focus of this paper, oblige a licensee to grant the right to future improvements in the licensed technology to a licensor of the seed technology (Shapiro, 1985). Since the clause enhances the appropriability attached to an initial innovator, the licensor's incentive can be preserved and reinforced. Conversely, the clause is criticized for enabling a licensor to gain a competitive advantage and establish a dominant position over licensees. This attractiveness of having the first patent-holding position is likely to urge firms to be actively engaged in competition for the initial innovation and thereby provide them with a strong incentive to invest in such innovation.

A few previous studies have addressed the effect of the grant-back clause on innovation incentives. [1] van Dijk (2000) focused on the social overincentive problem of R&D under technological competition, in which an incumbent and a challenger compete for innovation. The incumbent already has an initial technology that can be further innovated by both the incumbent and the challenger. Since both firms intend to innovate first (common pool externalities) and the challenger does not consider the incumbent's current profit (business-stealing externalities), their total R&D investment might be greater than the socially optimal level. The grant-back clause partially internalizes the common pool externalities to this overincentive problem. It makes these two firms accept that there is no need to devote excessive effort to the innovation because the incumbent is entitled to the outcome achieved by the challenger and the challenger has to share the outcome with the incumbent. Therefore, van Dijk (2000) lends support for the grant-back contract on the grounds that it reduces overinvestment in the innovation toward the socially optimal level.

Although stressing the role of the grant-back clause in solving the overincentive problem of follow-on innovation, van Dijk (2000) assumed that one firm had already achieved the initial innovation. In this regard, the incentive for the entire stream of innovation was not fully investigated. Unlike them, Hatanaka (2012) examined a game-theoretic model, in which two firms competed for both the initial and follow-on innovations. Her study critically lacked a comprehensive analysis of social welfare, however. As aforementioned, overinvestment in R&D could pose a serious problem by wasting research resources when several firms compete. It is therefore imperative to incorporate an evaluation of social welfare into the model.

This paper fills a gaps in these previous studies by developing a model that sheds light on the nature of both technological competition and cumulative innovation. Since we assume that both the initial and follow-on innovations are completely patentable and that more investments generate a higher probability of innovating first, the two firms compete with each other to be the first innovator of these two technologies. We demonstrate that because of the typical characteristics of technological competition, when consumer surplus obtained from cumulative innovation is negligible, the R&D investment is likely to be excessive compared to the socially optimal level. Given a negligible consumer surplus, technological competition wastes research resources and does not contribute to social welfare.

Now that patent systems exist in most developed countries, firms in high-tech industries have a strong tendency to seek an exclusionary patent right to their innovations. We can observe from business surveys that duplicative research can sometimes occur due to technological competition. The Ministry of Economy, Trade and Industry of Japan (2011), which reviewed the innovative activities of Japanese firms based on questionnaires, revealed that 61.8% of their R&D investment was considered duplicative with those of competitors in the same industries. Consequently, this paper's analysis will be useful in clarifying the situation,

[1] In addition to the theoretical studies described herein, see Leone and Reichstein (2012) and Laursen, Leone, Moreira, and Reichstein (2012) for empirical analyses of the grant-back clause.

in which R&D competition between firms is very prevalent.

Below are the brief intuitions that are addressed in this paper. This paper's main contribution is to compare innovation incentives in technological competition and cumulative innovation in accordance with various technological development schemes. When the consumer surplus is negligible, we demonstrate that there is generally a trade-off between incentives in cumulative innovation. If it is the intention to peg an investment in the follow-on technology to the socially optimal level by allowing a licensor to have exclusionary use of the initial technology, overinvestment in the initial technology is almost certain to deteriorate due to the increased attractiveness of this technology.

The focus is then directed particularly to the grant-back clause. We prove that a well-designed grant-back contract, which encompasses an appropriate profit distribution, can provide a better balance between these two innovations. That is, not only does the grant-back clause decreases investment in the follow-on technology, but it can also greatly reduce overinvestment in the initial technology, bringing it closer to the optimal level. If it is possible for the government to specify a particular profit distribution as a benefit of the grant-back contract, overinvestment in the initial technology can be reduced to the socially optimal level. These results extend the work of van Dijk (2000), who analyzed the effect of the grant-back clause solely on follow-on innovation.

This paper also examines the case in which an improved final product after both innovations creates a significantly positive consumer surplus, which seems to be a more plausible setting. This paper, then, documents the fact that technological competition for follow-on innovation can enhance social welfare by increasing the probability of a product emerging on the market that delivers benefit to consumers, and that the level of social welfare varies as the consumer surplus changes. This is a much broader view than the perspectives provided by previous authors, who make no reference to the relationship between technological development schemes and social welfare.

The reminder of this paper is organized as follows. Section 2 outlines the model of technological competition and cumulative innovation. Section 3 analyzes the technological development schemes in terms of the incentive to innovate and social welfare, in which the consumer surplus is negligible. Section 4 considers a significantly positive consumer surplus and highlights a different implication. Finally, Section 5 concludes, followed by and Appendix and the References.

2 The Model

Let us suppose that two firms, denoted by Firm 1 and Firm 2, compete for technologies and a product market. There are two types of technologies: "research" (denoted by R) and "development" (denoted by D). These "research" and "development" technologies correspond to the "initial" and "follow-on" technologies that were referred to in Section 1. Cumulative innovation is assumed to specify that technology R is a "research tool" essential for the next step in developing technology D, and that only the latter generates an improved final product. [2] Moreover, by postulating that both technologies R and D are completely patentable (i.e., have broad patent breadth), the possibility of imitation by rival firms is eliminated.

The model consists of the following three stages. [3] Figure 1 illustrates the timing of the decisions in this extensive-form game.

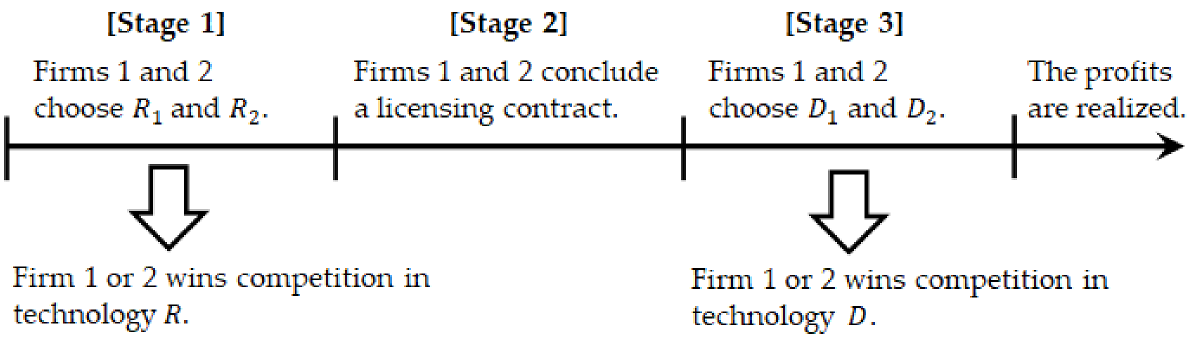

FIGURE 1 Timing of the model

Stage 1. Firms 1 and 2 choose their investment in technology R.
Stage 2. The firm that has achieved technology R appropriates it and does not license it, or discloses it through a licensing contract with (or without) a grant-back clause.
Stage 3. Firms 1 and 2 choose their investment in technology D.

In Stage 1, let R_i for $i = 1,2$ denote the investment in technology R conducted by firm i. Following van Dijk (2000), we formulate the probability of firm i achieving technology R as follows: $P_{R_i}(R_1,R_2) = \frac{R_i}{\sum_{n=1}^{2} R_n} = \frac{R_i}{R_i+R_j}$, $i,j = 1,2$, $i \neq j$. [4] If firm i increases its investment, the probability of firm j achieving technology R inevitably declines. In this regard, the firms are typically involved in technological competition seeking an exclusionary patent right to the initial innovation. As the possibility that both firms fail to develop technology R is excluded, there is no uncertainty in the initial innovation. Hereafter, we proceed by supposing that Firm 1 realizes technology R without any loss of generality.

In Stage 2, there are several cases to be considered independently. Firm 1 may withhold technology R and not transfer it to Firm 2 through a licensing contract. In this case, only Firm 1 has the opportunity to develop technology D and supply an improved final product to the market, whereas Firm 2 is forced to supply an existing, unimproved product. By contrast,

[2]The research tool model was reviewed by Hall (2007) and Rockett (2010).

[3]The timing follows Green and Scotchmer (1995), who supposed an *ex-ante* agreement that is reached before firms invest in the follow-on innovation.

[4]When it comes to the formulation of success probabilities, Denicolò (2000) assumed a Poisson discovery process instead.

Firm 1 may have to grant full access by disclosing technology R to Firm 2 as stipulated in a licensing contract. Lastly, Firm 1 may be able to employ technology D achieved by Firm 2 through a licensing contract with a grant-back clause. While Firm 1's decisions on technology transfer are not endogenously incorporated into the model, the respective analyses of these technological development schemes greatly facilitate the comparison of social welfare.

Let D_i denote the investment in technology D by firm i in Stage 3. Unlike technology R, we assume that uncertainty exists concerning whether technology D can be achieved. This assumption is distinct from Banal-Estañol and Macho-Stadler (2010), who posited that uncertainty was included in the initial innovation. The backdrop of our assumption is as follows. While basic innovations have been regarded as difficult to exploit in natural science, it has recently been said that the application phase in fields such as pharmaceuticals includes much more uncertainty. [5] Accordingly, this model analyzes innovative activities, in which a large degree of uncertainty is embedded in the follow-on innovation. Introducing an uncertainty factor, $u > 0$, the probability that firm i achieves technology D is formulated as follows: $P_{D_i}(D_1, D_2) = \frac{D_i}{\sum_{n=1}^{2} D_n + u} = \frac{D_i}{D_i + D_j + u}$, $i, j = 1, 2$, $i \neq j$. The probability that technology D is not developed by the two firms is represented as $P_{D_u} = \frac{u}{\sum_{n=1}^{2} D_n + u}$.

In the payoff stage following Stage 3, revenue is realized. If one firm achieves technology D and the other necessarily fails to do, the revenue of the former and the latter results in $\overline{\pi}$ and $\underline{\pi}$, respectively, with $\overline{\pi} > \underline{\pi}$. If both firms fail to achieve technology D, they are assumed to obtain the same revenue of π, with $\overline{\pi} > \pi > \underline{\pi}$, by sharing the product market symmetrically.

The third-stage profits of Firms 1 and 2 are defined as follows:

$$V_1 = P_{D_1}\overline{\pi} + P_{D_2}\underline{\pi} + P_{D_u}\pi - \alpha R_1 - \beta D_1 = \frac{D_1\overline{\pi} + D_2\underline{\pi} + u\pi}{\sum_{n=1}^{2} D_n + u} - \alpha R_1 - \beta D_1, \tag{1}$$

$$V_2 = P_{D_2}\overline{\pi} + P_{D_1}\underline{\pi} + P_{D_u}\pi - \alpha R_2 - \beta D_2 = \frac{D_2\overline{\pi} + D_1\underline{\pi} + u\pi}{\sum_{n=1}^{2} D_n + u} - \alpha R_2 - \beta D_2, \tag{2}$$

where $\alpha, \beta > 0$ are the common unit costs of developing technologies R and D, respectively. [6]

For numerical analysis, we set $\overline{\pi} = 2\pi$; the revenue obtained from an improved final product (2π) is the sum of each revenue obtained from sharing the product market with existing, unimproved products (π). This assumption implies that if a firm producing an

[5]For example, the drug development process is split into two phases: the initial phase of discovering the chemical compound candidates that have the potential to become new drugs and the follow-on phase of conducting clinical experiments that confirm their usefulness based on human trials. In general, as the interview results obtained by Saur-Amaral and Borges Gouveia (2007) show, the follow-on innovation seems to display much more uncertainty in the case of pharmaceuticals. In surveying the literature on uncertainty in innovation, Jalonen (2012) stressed the importance of classifying the causes of technological uncertainty into a lack of the knowledge regarding new technical details (i.e., basics) and a lack of the knowledge required to use this new technology (i.e., applications). Following this classification, our model focuses specifically on the latter cause.

[6]Although constant marginal costs are just one aspect of cost structures, this formulation makes reference to the existing studies such as van Dijk (2000) and Denicolò (2000).

improved final product can capture the entire market from its rival, it cannot extract any consumer surplus enhanced by an improved final product. [7] Although there may still be a concern about establishing a cartel that shares the monopoly profit, this assumption ($\overline{\pi} = 2\pi$) is set for the simplification of the following analyses. In addition, $\underline{\pi} = 0$ is posited in the model.

Based on this simplification, Equations (1) and (2) are rewritten as follows:

$$V_1 = \frac{(2D_1 + u)\pi}{D_1 + D_2 + u} - \alpha R_1 - \beta D_1, \tag{3}$$

$$V_2 = \frac{(2D_2 + u)\pi}{D_1 + D_2 + u} - \alpha R_2 - \beta D_2. \tag{4}$$

In the next section, the model based on Equations (3) and (4) will be investigated.

3 Equilibrium Investments in R&D

This section derives equilibrium of the model by backward induction. The model is further specified in line with technological development schemes regarding the transfer of the follow-on technology. Specifically, the following four cases are each considered independently: (i) a research joint venture (RJV); (ii) appropriation without technology transfer; (iii) a licensing contract without a grant-back clause; and (iv) a licensing contract with a grant-back clause. By comparing social welfare in the equilibria of these four cases, our argument is centered on the desirability of each technological development scheme. While Section 3 assumes that the consumer surplus (denoted by C) is negligible ($C = 0$), Section 4 regards it as significantly positive ($C > 0$).

3.1 RJV

As a benchmark case, we consider what the socially optimal investment in technology R might be. One plausible way to internalize the negative common pool externalities caused by technology competition is to form a single research entity, an RJV, at the stage of initial innovation. An RJV, which shares the initial innovation within firms as if it were a single entity, can keep its development cost at a minimum.

For analytical purposes, the timing of the game is specified as follows. Firms 1 and 2 form an RJV and achieve technology R (Stage 1), the RJV allows the two original firms to access technology R (Stage 2), and then they compete in seeking technology D (Stage 3). We assume that the RJV does not persist in Stage 3. [8]

[7] We assume that firms cannot always use their dominant position over consumers by engaging in things like price discrimination because the government may enforce regulations with the aim of protecting consumers.

[8] Tao and Wu (1997) and Miyagawa (2007) theoretically demonstrated that an RJV tends to lead to collusion

The third-stage profits of Firms 1 and 2, V_1^J and V_2^J, are given by Equations (3) and (4), respectively. We can obtain the following first-order conditions of maximizing V_1^J and V_2^J with regard to the investment in technology D as follows:

$$\frac{\partial V_1^J}{\partial D_1^J} = \frac{(2D_2^J + u)\pi}{(D_1^J + D_2^J + u)^2} - \beta = 0, \tag{5}$$

$$\frac{\partial V_2^J}{\partial D_2^J} = \frac{(2D_1^J + u)\pi}{(D_1^J + D_2^J + u)^2} - \beta = 0. \tag{6}$$

From Equations (5) and (6), $D_i^{J^*} = \frac{\pi - \beta u}{2\beta}$ for $i = 1, 2$ is the equilibrium investment ($D^{J^*} = \sum_{n=1}^{2} D_n^{J^*} = \frac{\pi - \beta u}{\beta}$), in which the second-order condition is satisfied. [9] The positivity condition, $D_i^{J^*} > 0$, is equivalent to $\frac{\pi}{\beta u} > 1$. In what follows, we analyze the model by positing that $\frac{\pi}{\beta u} > 1$ is always satisfied. It must also be the case that $V_i^{J^*} = \frac{(2D_i^* + u)\pi}{D_1^* + D_2^* + u} - \alpha R_i^J - \beta D_i^{J^*} = \frac{\pi + \beta u}{2} - \alpha R_i^J$ exceeds the profit, $V_i^{J^0} = \frac{2\beta u \pi}{\pi + \beta u} - \alpha R_i^J$, that is obtained when $D_i^J = 0$. As is easily shown, because $V_i^{J^*} - V_i^{J^0} = \frac{(\pi - \beta u)^2}{2(\pi + \beta u)} > 0$, we always have $V_i^{J^*} > V_i^{J^0}$ under $\frac{\pi}{\beta u} > 1$, which guarantees that $D_i^{J^*}$ is an equilibrium.

Let us revert to Stage 1, in which both firms form an RJV. The joint profit of the RJV equals $\Omega^J = \sum_{n=1}^{2} V_n^{J^*} = \pi + \beta u - \alpha R^J$, where $R^J = \sum_{n=1}^{2} R_n^J$. This means that the lower the investment in technology R, the higher the profit of the RJV. From this, the RJV finds it optimal to cut its investment to the extreme limit, while still maintaining a level that results in technology R being innovated. The interpretation is that only "tackling" the research process matters to innovate technology R, and further investments are a mere waste. Stated more generally, the RJV is likely to set $R^{J^*} = \varepsilon > 0$, where ε is the minimum research investment that is necessary to achieve technology R. In the current model, ε can be infinitesimally small. This infinitesimal investment does not lose any generality if we regard it as the essential minimum investment required to achieve the initial innovation. [10]

This result suggests that an RJV, analogous to a single entity, is the most conducive innovative system in developing the initial technology when technological competition is subject to a waste of research resources. If there are many firms competing for the initial innovation in the absence of uncertainty, common pool externalities arise, which suggests that the investments of multiple firms become totally duplicative. In the related studies, Kamien,

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in the downstream product market. However, such collusion may be rejected by the government, which has little sympathy toward integrated firms within the full sequence of innovations.

[9] From Equation (5), we obtain $\frac{\partial^2 V_1^J}{\partial (D_1^J)^2} = -\frac{2\pi(2D_2^J + u)}{(D_1^J + D_2^J + u)^3} = -2\beta < 0$ for $D_1^{J^*} = D_2^{J^*} = \frac{\pi - \beta u}{2\beta}$. The second-order condition is also the case with Equation (6).

[10] It is also feasible to posit that a significant amount of the investment, $\underline{R} > \varepsilon$, is required for the achievement of technology R. If we define a minimal required amount of the initial investment as significantly positive in this way, an implicit assumption is necessary – that the initial investment derived in later cases is also sufficiently large that it always exceeds $\underline{R}$.

Muller, and Zang (1992) point to a similar issue, in which an RJV sharing its R&D investment economizes scarce resources and generates higher profits in a Cournot-type downstream market.

3.2 Appropriation without technology transfer

This subsection establishes the socially optimal level of investment in technology D. The setting is such that while appropriating technology R, Firm 1 does not transfer it to Firm 2. Accordingly, while only Firm 1 has the opportunity to proceed to the follow-on innovation, Firm 2 is not eligible to do so.

Let us denote V_i^A as the third-stage profit of firm i for $i = 1, 2$:

$$V_1^A = \frac{(2D_1^A + u)\pi}{D_1^A + u} - \alpha R_1^A - \beta D_1^A, \tag{7}$$

$$V_2^A = \frac{u\pi}{D_1^A + u} - \alpha R_2^A. \tag{8}$$

Note that $D_2^{A^*} = 0$ in Equation (8). From Equation (7), the first-order condition of Firm 1 is $\frac{\partial V_1^A}{\partial D_1^A} = \frac{u\pi}{(D_1^A+u)^2} - \beta = 0$. This provides the optimal investment in technology D by Firm 1 with $D_1^{A^*} = \sqrt{\frac{u\pi}{\beta}} - u > 0$ (naturally, $D^{A^*} = \sum_{n=1}^{2} D_n^{A^*} = D_1^{A^*}$). [11]

As $D^{A^*} < D^{J^*}$ can be demonstrated, the total investment in technology D is less than that of the RJV. In our model, appropriation of the initial innovation by a single firm is the best way to mitigate the common pool externalities caused by follow-on competition because it nullifies the potential competitive investment (in this case, by Firm 2). In essence, this optimal investment in the follow-on innovation exactly corresponds to the one that van Dijk (2000) derived. Actually, this logic is the same in the analysis of the initial innovation previously discussed in the RJV case. Nevertheless, this result is critically dependent on the assumption that the consumer surplus equals zero. If a significantly positive consumer surplus is explicitly introduced in this model, then the current argument should be modified.

Now, we consider another possibility – that Firm 2 wins the initial competition. Let us represent $\tilde{V}_1^{A^*}$ as the profit of Firm 1 when it fails to achieve technology R. From the symmetry, we can derive $\tilde{V}_1^{A^*} = \frac{u\pi}{\tilde{D}_2^{A^*}+u} - \alpha R_1^A$ with $\tilde{D}_2^{A^*} = D_1^{A^*} = \sqrt{\frac{u\pi}{\beta}} - u$.

Stage 2 is omitted since the initial technology is appropriated by a single firm. The first-

[11] $V_1^{A^*} = \frac{(2D_1^{A^*}+u)\pi}{D_1^{A^*}+u} - \alpha R_1^A - \beta D_1^{A^*} = 2\pi + \beta u - 2\sqrt{\beta u \pi} - \alpha R_1^A$ is greater than $V_1^{A^0} = \pi - \alpha R_1^A$, which is obtained when $D_1^A = 0$ because $V^{A^*} - V^{A_1^0} = \pi + \beta u - 2\sqrt{\beta u \pi} = (\sqrt{\pi} - \sqrt{\beta u})^2 > 0$. Therefore, Firm 1 never opts for $D_1^A = 0$ when it possesses technology R.

stage profit of Firm 1, Ω_1^A, is given as follows:

$$\begin{aligned}\Omega_1^A &= P_{R_1}(R_1^A, R_2^A)V_1^{A^*} + P_{R_2}(R_1^A, R_2^A)\tilde{V}_1^{A^*} \\ &= \frac{R_1^A}{R_1^A + R_2^A}\left[\frac{(2D_1^{A^*} + u)\pi}{D_1^{A^*} + u} - \alpha R_1^A - \beta D_1^{A^*}\right] + \frac{R_2^A}{R_1^A + R_2^A}\left(\frac{u\pi}{D_1^{A^*} + u} - \alpha R_1^A\right).\end{aligned}$$

The first-order condition with regard to R_1^A is $\frac{\partial \Omega_1^A}{\partial R_1^A} = \frac{R_2^A}{(R_1^A+R_2^A)^2}\left(\frac{2D_1^{A^*}\pi}{D_1^{A^*}+u} - \beta D_1^{A^*}\right) - \alpha = 0$. The second-order condition is also satisfied for $\frac{\pi}{\beta u} > 1$. [12] Since $R_1^{A^*} = R_2^{A^*}$ at equilibrium due to symmetry, $R_i^{A^*} = \frac{1}{4\alpha}\left(\frac{2D_1^{A^*}\pi}{D_1^{A^*}+u} - \beta D_1^{A^*}\right) = \frac{2\pi+\beta u-3\sqrt{\beta u\pi}}{4\alpha}$ for $i = 1, 2$ ($R^{A^*} = \sum_{n=1}^{2} R_n^{A^*} = \frac{2\pi+\beta u-3\sqrt{\beta u\pi}}{2\alpha}$). The assumption that $\frac{\pi}{\beta u} > 1$ ensures that $R_1^{A^*}$ is strictly positive. Since $R^{A^*} > R^{J^*}$ generally holds, there is an overinvestment in technology R. This is because the firms seek an exclusionary patent right to the use of technology R.

Lemma 1. Comparing the total investment in technology R and D between the "RJV" and the "appropriation without technology transfer" cases, we obtain (1) $R^{J^*} < R^{A^*}$ and (2) $D^{J^*} > D^{A^*}$, respectively.

Lemma 1 shows that appropriating the initial technology generates a trade-off; while it leads to the socially optimal investment in the follow-on innovation, it generates social overinvestment in the initial innovation.

3.3 Licensing contract without a grant-back clause

In this subsection, we investigate the case in which one firm, achieving technology R, collects a licensing fee from the other in return for transferring technology R.

Such a licensing contract may not be voluntarily offered by the owner firm of the initial innovation unless it benefits from licensing in comparison with sole appropriation. In the current setup, it is quite evident that the owner firm does not have any motive to transfer its initial innovation to the other because the follow-on competition never fails to undermine its profit, even after a payment negotiation that is totally favorable to the firm.

Nevertheless, we assume that the licensing contract between these two firms can be enforceable. There are three plausible reasons why we assume that such a "compulsory" licensing contract is required from a policy perspective. First, a licensing contract can reduce the overincentive for the initial innovation and prevent research resources from being wasted. Second, it improves social welfare by increasing the probability of an improved final product emerging on the market. Third, a licensed firm is expected to enlarge the product market that

[12] $\frac{\partial^2 \Omega_1^A}{\partial (R_1^A)^2} = -\frac{2R_2^A}{(R_1^A+R_2^A)^3}\left(\frac{2D_1^{A^*}\pi}{D_1^{A^*}+u} - \beta D_1^{A^*}\right) = -\frac{R_2^A(2\pi+\beta u-3\sqrt{\beta u\pi})}{(R_1^A+R_2^A)^2} = -\frac{R_2^A[(\sqrt{\pi}-\sqrt{\beta u})^2+\sqrt{\pi}(\sqrt{\pi}-\sqrt{\beta u})]}{(R_1^A+R_2^A)^2} < 0$ for $\frac{\pi}{\beta u} > 1$. In later cases, investigations of the second-order condition will be omitted to save spaces.

a licensor cannot reach (van Dijk, 2000). Only the first reason is highlighted and the second and third are not taken into account at present. [13]

The licensing fee is assumed to be a fixed amount, f^L. Let us also assume that Firm 1 must guarantee to Firm 2 at least the least profit that is obtained when technology R is not transferred. That is, we restrict attention in this model to the licensing fee that is acceptable to the licensee, which can be also the best for the licensor.

Then, the third-stage profits of Firms 1 and 2 are defined as follows:

$$V_1^L = \frac{(2D_1^L + u)\pi}{D_1^L + D_2^L + u} - \alpha R_1^L - \beta D_1^L + f^L, \tag{9}$$

$$V_2^L = \frac{(2D_2^L + u)\pi}{D_1^L + D_2^L + u} - \alpha R_2^L - \beta D_2^L - f^L. \tag{10}$$

Since the equilibrium in Stage 3 is independent of f^L, it is the same with what was obtained from Equations (3) and (4): $D_i^{L^*} = D_i^{J^*} = \frac{\pi - \beta u}{2\beta}$ for $i = 1, 2$. Plugging them into Equations (9) and (10) yields $V_1^{L^*} = \frac{\pi+\beta u}{2} - \alpha R_1^L + f^L$ and $V_2^{L^*} = \frac{\pi+\beta u}{2} - \alpha R_2^L - f^L$, respectively.

Turning back to Stage 2, Firm 1 transfers technology R and simultaneously negotiates a licensing fee, f^L, with Firm 2. From Equation (10), the minimum third-stage profit of Firm 2 is equal to $\hat{V}_2^{A^*} = \sqrt{\beta u \pi} - \alpha R_2^L$. Assuming that Firm 2 accepts the licensing contract, which induces the same profit as appropriation without technology transfer, we can derive f^{L^*} such that $f^{L^*} = \frac{(\sqrt{\pi} - \sqrt{\beta u})^2}{2} > 0$.

In Stage 1, if Firm 1 fails to achieve technology R, its profit results in $\tilde{V}_1^{L^*} = \pi - \alpha R_1^L - \beta D_1^{L^*} - f^{L^*}$. As a result, Firm 1 maximizes the following first-stage profit with regard to R_1^L:

$$\Omega_1^L = P_{R_1}(R_1^L, R_2^L) V_1^{L^*} + P_{R_2}(R_1^L, R_2^L) \tilde{V}_1^{L^*} = \pi - \alpha R_1^L - \beta D_1^{L^*} + \left(\frac{R_1^L - R_2^L}{R_1^L + R_2^L} \right) f^{L^*}.$$

The first-order condition is $\frac{\partial \Omega^L}{\partial R_1^L} = \frac{2R_2^L f^{L^*}}{(R_1^L + R_2^L)^2} - \alpha = 0$. Since $R_1^{L^*} = R_2^{L^*}$, we obtain $R_i^{L^*} = \frac{f^{L^*}}{2\alpha} = \frac{(\sqrt{\pi} - \sqrt{\beta u})^2}{4\alpha} > 0$ for $i = 1, 2$ ($R^{L^*} = \sum_{n=1}^{2} R_n^{L^*} = \frac{(\sqrt{\pi} - \sqrt{\beta u})^2}{2\alpha}$).

Lemma 2. Comparing the total investments in technology R and D between the "appropriation without technology transfer" and the "licensing contract without a grant-back clause" cases, we obtain (1) $R^{L^*} < R^{A^*}$ and (2) $D^{A^*} < D^{L^*}$, respectively.

Since the firms are guaranteed to utilize technology R through the licensing contract, the overincentive to achieve the initial innovation is weakened. Concurrently, this overincentive is not entirely internalized because the firms still intend to extract a licensing fee as the

[13] Section 4 analyzes the second reason by varying a positive consumer surplus.

licensor and avoid paying a costly licensing fee as the licensee. Conversely, since the firms compete to develop an improved final product, the total investment in technology D is sure to exceed the optimal level. Importantly, this analysis makes it clear that the follow-on innovation scheme affects the initial innovation incentives. The other important point is that the licensing contract without a grant-back clause is always inferior to the RJV that optimizes (minimizes) the investment in technology R. While the degree of competition in technology D is the same across these two schemes, the RJV undertakes less investment in technology R.

3.4 Licensing contract with a grant-back clause

We examine whether a licensing contract with a grant-back clause resolves or mitigates this trade-off problem. As will be demonstrated, a grant-back clause, which allows an initial innovator to access the follow-on innovation possessed by another, is likely to alter the incentives of firms for the whole sequence of cumulative innovation. [14]

Three types of grant-back clauses are analyzed: (i) graont-back contract with a licensing fee; (ii) grant-back contract with a Nash bargaining solution; and (iii) optimal grant-back contract. In practice, grant-back clauses take on different forms, and the implications for innovation incentives and social welfare therein could also vary.

3.4.1 Grant-back contract with a licensing fee

In the case of a grant-back contract with a licensing fee, Firm 1 is assumed to collect a licensing fee as well as receive a grant-back of the follow-on innovation while exclusively possessing the initial innovation. In the sense that Firm 2 is not compensated for the follow-on innovation, the distribution of profits could be biased toward Firm 1.

Despite the grant-back clause, Firm 2 is still eligible to employ technology D. [15] Therefore, both firms share the product market equally, earning the equivalent revenue, π, due to an identically improved final product. The equivalent revenue assumption implies that there are no changes made to the fundamental product market structure, even after cumulative innovation is achieved.

[14] A grant-back clause is typically regulated in accordance with the attributes of follow-on innovation in countries such as those in the European Union. Ambashi, Régibeau, and Rockett (2019) examined the validity of grant-back contracts within a cumulative innovation model characterized by the attributes of follow-on innovation.

[15] If the grant-back clause prohibits Firm 2 from using its own technology D, Firm 2 loses all incentive to invest in that technology, so the model would be reduced to the appropriation without technology transfer case discussed in Subsection 3.2. Antitrust law generally stipulates that licensing contracts which totally prohibit licensees from using their improved innovations are regarded as an unfair trade practice.

The third-stage profits, V_1^G and V_2^G, are defined as follows:

$$V_1^G = \frac{(2D_1^G + D_2^G + u)\pi}{D_1^G + D_2^G + u} - \alpha R_1^G - \beta D_1^G + f^G, \tag{11}$$

$$V_2^G = \frac{(D_2^G + u)\pi}{D_1^G + D_2^G + u} - \alpha R_2^G - \beta D_2^G - f^G. \tag{12}$$

The first-order conditions of Equations (11) and (12) are, respectively:

$$\frac{\partial V_1^G}{\partial D_1^G} = \frac{(D_2^G + u)\pi}{(D_1^G + D_2^G + u)^2} - \beta = 0, \tag{13}$$

$$\frac{\partial V_2^G}{\partial D_2^G} = \frac{D_1^G \pi}{(D_1^G + D_2^G + u)^2} - \beta = 0. \tag{14}$$

Based on $D_1^G = D_2^G + u$ from Equations (13) and (14), we obtain $D_1^{G^*} = \frac{\pi}{4\beta}$, $D_2^{G^*} = \frac{\pi - 4\beta u}{4\beta} < D_1^{G^*}$, and $D^{G^*} = \sum_{n=1}^{2} D_n^{G^*} = \frac{\pi - 2\beta u}{2\beta}$.[16] Whereas $D_1^{G^*} > 0$ always holds, $D_2^{G^*} > 0$ holds only for $\frac{\pi}{\beta u} > 4$. Conversely, $D_2^{G^*} = 0$ under $1 < \frac{\pi}{\beta u} < 4$. For the purpose of analysis, $\frac{\pi}{\beta u} > 4$ is assumed, which implies that the grant-back contract needs to come into effect. Notably, the grant-back contract leads both Firms 1 and 2 to make smaller investments in technology D than in the case of a licensing contract without a grant-back clause because $D_1^{L^*} - D_1^{G^*} = \frac{\pi - 2\beta u}{4\beta} > 0$ and $D_2^{L^*} - D_2^{G^*} = \frac{\pi + 2\beta u}{4\beta} > 0$, respectively.

In Stage 2, Firm 1 is likely to set a licensing fee, f^G, that ensures the minimum third-stage profit of Firm 2. As we have seen, this profit equals $\hat{V}_2^{A^*} = \hat{V}_2^{L^*} = \sqrt{\beta u \pi} - \alpha R_2^G$. Therefore, f^G is determined such that $V_2^{G^*} = \hat{V}_2^{A^*} \Rightarrow f^{G^*} = \frac{(\sqrt{\pi} - 2\sqrt{\beta u})^2}{4} > 0$.

Turn back to Stage 1. If Firm 1 fails to achieve technology R, the profit should be $\tilde{V}_1^{G^*} = \frac{(\tilde{D}_1^{G^*} + u)\pi}{\tilde{D}_1^{G^*} + \tilde{D}_2^{G^*} + u} - \alpha R_1^G - \beta \tilde{D}_1^{G^*} - f^{G^*}$, where $\tilde{D}_1^{G^*} = D_2^{G^*} = \frac{\pi - 4\beta u}{4\beta}$ and $\tilde{D}_2^{G^*} = D_1^{G^*} = \frac{\pi}{4\beta}$. Consequently, the first-stage profit of Firm 1 is provided by:

$$\begin{aligned}\Omega_1^G &= P_{R_1}(R_1^G, R_2^G) V_1^{G^*} + P_{R_2}(R_1^G, R_2^G) \tilde{V}_1^{G^*} \\ &= \frac{R_1^G}{R_1^G + R_2^G}\left[\frac{(2D_1^{G^*} + D_2^{G^*} + u)\pi}{D_1^{G^*} + D_2^{G^*} + u} - \alpha R_1^G - \beta D_1^{G^*} + f^{G^*}\right] \\ &+ \frac{R_2^G}{R_1^G + R_2^G}\left[\frac{(\tilde{D}_1^{G^*} + u)\pi}{\tilde{D}_1^{G^*} + \tilde{D}_2^{G^*} + u} - \alpha R_1^G - \beta \tilde{D}_1^{G^*} - f^{G^*}\right].\end{aligned}$$

The first-order condition is $\frac{\partial \Omega_1^G}{\partial R_1^G} = \frac{R_2^G}{(R_1^G + R_2^G)^2}\left[\frac{2D_1^{G^*}\pi}{D_1^{G^*} + D_2^{G^*} + u} - \beta(D_1^{G^*} - D_2^{G^*}) + 2f^{G^*}\right] - \alpha = 0$. Since $R_1^{G^*} = R_2^{G^*}$, the equilibrium investment in technology R is $R_i^{G^*} = \frac{\pi - \beta u + 2f^{G^*}}{4\alpha} = \frac{3\pi + 2\beta u - 4\sqrt{\beta u \pi}}{8\alpha} > 0$ for

[16] The negative roots are eliminated by the non-negativity condition.

$i = 1, 2$ ($R^{G^*} = \sum_{i=1}^{2} R_i^{G^*} = \frac{3\pi + 2\beta u - 4\sqrt{\beta u \pi}}{4\alpha}$).

Proposition 1 compares the the investments of the licensing contract that includes a grant-back clause with a licensing fee and the other schemes analyzed up until this point.

Proposition 1. With regard to the total investments in technologies R and D, we obtain (1) $R^{A^*} > R^{G^*} > R^{L^*} > R^{J^*}$ and (2) $D^{L^*} = D^{J^*} > D^{G^*} > D^{A^*}$.

The overincentive for the follow-on innovation (technology D) is mitigated to a certain degree by the use of a grant-back clause. The first reason is that the licensor has the expectation of having access to the follow-on innovation, even if it fails to develop it. The second reason is that the licensee ends up decreasing his or her incentive by gaining a lower profit by transferring the follow-on innovation to the licensor. All in all, a grant-back clause partially internalizes the potential overinvestment in the follow-on innovation, which is the economic mechanism that van Dijk (2000) pointed out.

By contrast, our model derives an implication for the initial innovation as well. Although this type of grant-back clause is sure to reduce the overincentive for the initial innovation (technology R), the degree of internalization is lower than that of the licensing contract without a grant-back clause. Since the firms are expected to receive a grant-back of the follow-on innovation without any payment to the other when they are a licensor, winning technological competition for the initial innovation and retaining a grant-back is rather attractive. This "reward" yielded to the licensor makes the overincentive for the initial innovation further deteriorate. Such finding suggests that the investment in the initial innovation can differ along with the distribution of profits obtained from the grant-back contract.

3.4.2 Grant-back contract with a Nash bargaining solution

The following analysis assumes that the government can encourage firms to negotiate the distribution of profits based upon a Nash bargaining solution (Nash, 1950; Osborne & Rubinstein, 1990). This assumption of government intervention is not systematic but exogenous. However, it allows us to accentuate the diversity of grant-back contracts that could vary the profit distribution.

The outside option as disagreement points, is assumed to be the licensing contract without a grant-back clause discussed in Subsection 3.3. [17] In other words, the use of a grant-back clause is allowed solely in the environment in which the licensing contract is really concluded to transfer the initial technology, which is plausible from the perspective of the government that intends to strengthen the stream of cumulative innovation. Accordingly, when Firm 1

[17] Generally we can distinguish a "bargaining position" from "bargaining power" when discussing the profit distribution through negotiation. There exist disagreement points at which the solutions based on these two ideas can coincide. However, since we assume exogenous and fixed government intervention, the idea of a bargaining position on the basis of the disagreement points is used in this paper.

achieves technology R, the disagreement points of Firms 1 and 2 are $\hat{V}_1^{L^*} = \pi + \beta u - \sqrt{\beta u \pi} - \alpha R_1^N$ and $\hat{V}_2^{L^*} = \sqrt{\beta u \pi} - \alpha R_2^N$, respectively. Since $\hat{V}_1^{G^*} = \frac{5\pi}{4} - \alpha R_1^N$ and $\hat{V}_2^{G^*} = \frac{\pi}{4} + \beta u - \alpha R_2^N$ as for the third-stage profits, the feasible set of the bargaining is as follows: [18]

$$\sum_{n=1}^{2} V_n^N = \sum_{n=1}^{2} \hat{V}_n^{G^*} = \frac{3\pi}{2} + \beta u - \alpha \left(\sum_{n=1}^{2} R_n^N \right) \text{ subject to } V_1^N \geq \hat{V}_1^{L^*},\ V_2^N \geq \hat{V}_2^{L^*}.$$

Then, we can derive the Nash bargaining solution from the following problem:

$$\max_{V_1^N, V_2^N} (V_1^N - V_1^{L^*})(V_2^N - V_2^{L^*}) \text{ subject to } \sum_{n=1}^{2} V_n^N = \sum_{n=1}^{2} \hat{V}_n^{G^*} = \frac{3\pi}{2} + \beta u - \alpha \left(\sum_{n=1}^{2} R_n^N \right).$$

This yields:

$$V_1^{N^*} = \frac{\sum_{n=1}^{2} \hat{V}_n^{G^*} + (\hat{V}_1^{L^*} - \hat{V}_2^{L^*})}{2} = \frac{5\pi}{4} + \beta u - \sqrt{\beta u \pi} - \alpha R_1^N,$$
$$V_2^{N^*} = \frac{\sum_{n=1}^{2} \hat{V}_n^{G^*} + (\hat{V}_2^{L^*} - \hat{V}_1^{L^*})}{2} = \frac{\pi}{4} + \sqrt{\beta u \pi} - \alpha R_2^N.$$

Let us denote $\tilde{V}_1^{N^*} = \frac{\pi}{4} + \sqrt{\beta u \pi} - \alpha R_1^N$ as the third-stage profit when Firm 1 fails to achieve technology R. The first-stage profit of Firm 1 is as follows:

$$\begin{aligned} \Omega_1^N &= P_{R_1}(R_1^N, R_2^N) V_1^{N^*} + P_{R_2}(R_1^N, R_2^N) \tilde{V}_1^{N^*} \\ &= \frac{R_1^N}{R_1^N + R_2^N} \left(\frac{5\pi}{4} + \beta u - \sqrt{\beta u \pi} - \alpha R_1^N \right) + \frac{R_2^N}{R_1^N + R_2^N} \left(\frac{\pi}{4} + \sqrt{\beta u \pi} - \alpha R_1^N \right). \end{aligned}$$

The first-order condition with regard to R_1^N is $\frac{\partial \Omega_1^N}{\partial R_1^N} = \frac{R_2^N}{(R_1^N + R_2^N)^2}(\pi + \beta u - 2\sqrt{\beta u \pi}) - \alpha = 0$. Then, we obtain the equilibrium, $R_i^{N^*} = \frac{\pi + \beta u - 2\sqrt{\beta u \pi}}{4\alpha} = \frac{(\sqrt{\pi} - \sqrt{\beta u})^2}{4\alpha} > 0$ for $i = 1, 2$ ($R^{N^*} = \sum_{i=1}^{2} R_i^{N^*} = \frac{(\sqrt{\pi} - \sqrt{\beta u})^2}{2\alpha}$). It is intuitively natural that $R_i^{N^*} = R_i^{L^*}$ should hold. Namely, the investment in technology R is equivalent to that generated by the licensing contract without a grant-back clause, because the "bottom-line" first-stage profits (i.e., the disagreement points) are also equivalent for these two firms.

Since $R^{L^*} < R^{G^*}$ from Proposition 1, we reach Proposition 2 as follows.

Proposition 2. With regard to the investment in technology R, we obtain $R^{N^*} = R^{L^*} < R^{G^*}$.

[18] The appropriation of technology R is assumed to be unavailable to the licensor. If it is available to the licensor as an outside option, the Nash bargaining solution can never be derived because the profit of the licensor earned by appropriation always exceeds that realized by a licensing contract with a grant-back clause. More concretely, we can demonstrate that $\sum_{n=1}^{2} V_n^N = \frac{3\pi}{2} + \beta u - \alpha(\sum_{n=1}^{2} R_n^N) < \sum_{n=1}^{2} V_n^{A^*} = 2\pi + \beta u - \sqrt{\beta u \pi} - \alpha(\sum_{n=1}^{2} R_n^N)$ for $\frac{\pi}{\beta u} > 4$.

The grant-back contract associated with the Nash bargaining solution reduces overinvestment in the initial innovation more than the grant-back clause with a licensing fee by adjusting the profit distribution to the licensee . Bearing in mind the previous result, $D^{N^*} = D^{G^*} < D^{L^*}$, as shown in Proposition 1 (2), we can expect that the licensing contract with a grant-back clause induced by the cooperative negotiation produces a more desirable result than the licensing contract without a grant-back clause.

3.4.3 Optimal grant-back contract

In the Nash bargaining solution, the total net surplus from the grant-back, $S^* = \sum_{n=1}^{2} \hat{V}_n^{G^*} - \sum_{n=1}^{2} \hat{V}_n^{L^*} = \frac{\pi}{2}$, was equally divided between the two firms. Now, suppose that the bargaining position is not necessarily equivalent between them. To this end, we define a new parameter, $k \in [0,1]$, as representing a licensor's bargaining position, where the larger the k, the stronger (weaker) the licensor's (licensee's) bargaining position.

When Firm 1 achieves technology R, the third-stage profits are as follows:

$$V_1^{O^*} = \hat{V}_1^{L^*} + kS^* = \frac{(k+2)\pi}{2} + \beta u - \sqrt{\beta u \pi} - \alpha R_1^O,$$
$$V_2^{O^*} = \hat{V}_2^{L^*} + (1-k)S^* = \frac{(1-k)\pi}{2} + \sqrt{\beta u \pi} - \alpha R_2^O.$$

Let $\tilde{V}_1^{O^*} = \frac{(1-k)\pi}{2} + \sqrt{\beta u \pi} - \alpha R_1^O$ denote the profit when Firm 1 fails to achieve technology R. The first-stage expected profit of Firm 1 is as follows:

$$\begin{aligned}\Omega_1^O &= P_{R_1}(R_1^O, R_2^O)V_1^{O^*} + P_{R_2}(R_1^O, R_2^O)\tilde{V}_1^{O^*} \\ &= \frac{R_1^O}{R_1^O + R_2^O}\left[\frac{(k+2)\pi}{2} + \beta u - \sqrt{\beta u \pi} - \alpha R_1^O\right] + \frac{R_2^O}{R_1^O + R_2^O}\left[\frac{(1-k)\pi}{2} + \sqrt{\beta u \pi} - \alpha R_1^O\right].\end{aligned}$$

The first-order condition is $R_i^{O^*}(k) = \frac{(\frac{2k+1}{2})\pi + \beta u - 2\sqrt{\beta u \pi}}{4\alpha}$ for $i = 1, 2$, which is increasing in k ($R^{O^*}(k) = \sum_{n=1}^{2} R_n^{O^*}(k) = \frac{(2k+1)\pi + 2\beta u - 4\sqrt{\beta u \pi}}{4\alpha}$). In other words, the greater the fraction of the distribution given to the licensor, the greater the investment in technology R.

See Figure 2 regarding the diagram of $R^{O^*}(k)$. $k = 1$ and $\frac{1}{2}$ correspond to the grant-back contract with a licensing fee and that with a Nash bargaining solution, respectively.

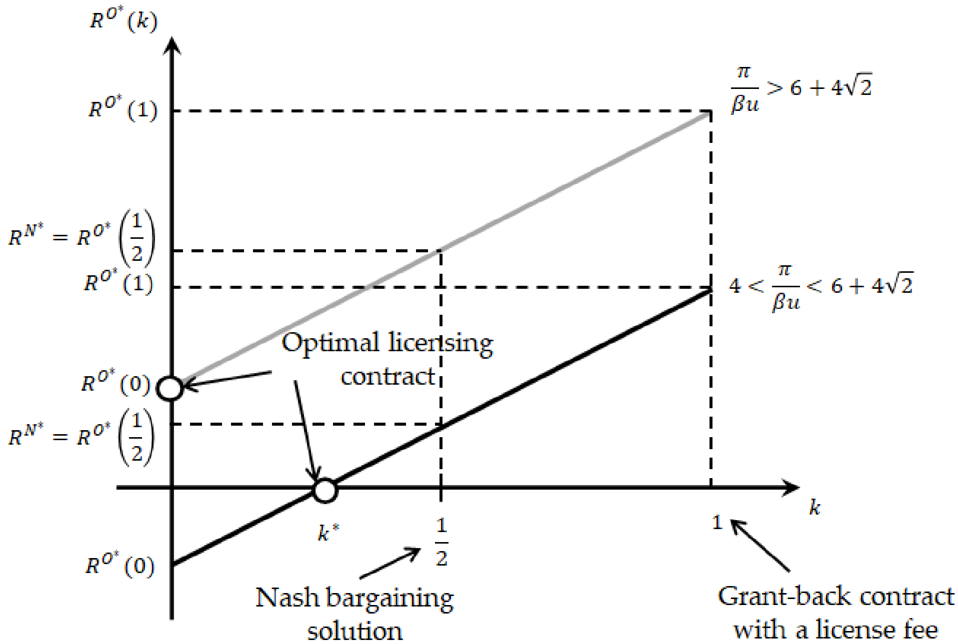


FIGURE 2 Diagram of $R^{O^*}(k)$

From these discussions, we can find a distribution that provides the optimal investment in technology R. Proposition 3 summarizes the result.

Proposition 3. (1) If it is possible to specify a particular distribution of profits obtained from concluding the contract with a grant-back clause, the optimal investment in technology R can be achieved with an infinitesimal positive value as follows: $R^{O^*} = \varepsilon$ (for $4 < \frac{\pi}{\beta u} < 6 + 4\sqrt{2}$) and $R^{O^*} = \frac{\pi + 2\beta u - 4\sqrt{\beta u \pi}}{4\alpha}$ (for $\frac{\pi}{\beta u} > 6 + 4\sqrt{2}$); and
(2) The Nash bargaining solution ($R^{N^*} = \frac{\pi + \beta u - 2\sqrt{\beta u \pi}}{2\alpha}$) still gives the licensor an overincentive to invest in technology R as compared to the optimal investment level.

See Figure 2 once again. When $4 < \frac{\pi}{\beta u} < 6 + 4\sqrt{2}$ ($\simeq 11.657$), the optimal distribution is approximated by $k^{O^*} \approx k^* = \frac{-\pi - 2\beta u + 4\sqrt{\beta u \pi}}{2\pi} \in (0, \frac{1}{2})$. If this distribution is possible, the investment in technology R can be set to the optimal level, $R^{O^*}(k^{O^*}) = \varepsilon$. On the other hand, when $\frac{\pi}{\beta u} > 6 + 4\sqrt{2} > 4$, it is optimal to set $k^{O^*} = 0$ ($R^{O^*}(0) = \frac{\pi + 2\beta u - 4\sqrt{\beta u \pi}}{4\alpha} > 0$), a point at which the licensee should be entitled to receive the entire distribution.

Proposition 3 is analogous to van Dijk's (2000) implication about an *ex-post* licensing fee regarding the adjustment of the investment in the follow-on innovation. Contrastingly, our model proposes that an *ex-post* arrangement for the appropriate profit distribution can lead to the optimal incentive to innovate the initial innovation. Our model suggests that although the types of grant-back clauses themselves do not have any effect on the investment in the follow-on innovation, the future distribution can directly affect the incentives to invest in the initial innovation by changing the attractiveness of receiving a grant-back as a licensor. Importantly, just as van Dijk (2000) mentioned, the optimal investment in the initial innovation cannot be achieved solely by the inclusion of a grant-back clause into a licensing contract, but rather, through a cleverly chosen distribution of future profits.

The aforementioned argument is critical from the perspective of innovation policy. For example, the European Union (2004) expressed a serious concern about the accumulation of too strong a position of a licensor on the grounds that a grant-back clause may impose an unfair trade practice on a licensee. On the other hand, we discover another precaution for the use of a grant-back clause; the overincentive to achieve the initial innovation may be exacerbated through a pronounced patent right being attached to a licensor. It is therefore desirable that the benefit attached to a licensor should be adjusted to the optimal level to prevent excessive technological competition for the initial innovation.

However, it is not guaranteed that firms successfully conclude a contract with the inclusion of a grant-back clause that specifies the optimal investment in the initial technology. One reason is that firms may not be able to reach an *ex-ante* agreement with such a contract before the distribution due to an imperfectly drawn-up contract. For this reason, there seems to be some role for government intervention in formulating grant-back contracts and dividing up profits obtained from them.

3.5 Comparison of social welfare

To sum up the discussions in this section, social welfare is compared in relation to each technological development scheme. Under the premise that consumer surplus is negligible, the sum of the firms' profits is simply regarded as social welfare. Accordingly, social welfare in each scheme is denoted by $\Omega^{X^*} = \sum_{n=1}^{2} \Omega_n^{X^*}$, with $X^* = J, A, L, G, N$, and O. Table 1 below represents social welfare in each scheme.

TABLE 1 Optimal investment and social welfare with a negligible consumer surplus

RJV	$R^{J^*} = \varepsilon$	$D^{J^*} = \frac{\pi-\beta u}{\beta}$	$\Omega^{J^*} \approx \pi + \beta u$
Appropriation	$R^{A^*} = \frac{2\pi+\beta u-3\sqrt{\beta u\pi}}{2\alpha}$	$D^{A^*} = \sqrt{\frac{u\pi}{\beta}} - u$	$\Omega^{A^*} = \frac{2\pi+\beta u+\sqrt{\beta u\pi}}{2}$
License without GB	$R^{L^*} = \frac{\pi+\beta u-2\sqrt{\beta u\pi}}{2\alpha}$	$D^{L^*} = \frac{\pi-\beta u}{\beta}$	$\Omega^{L^*} = \frac{\pi+\beta u+2\sqrt{\beta u\pi}}{2}$
GB (licensing fee)	$R^{G^*} = \frac{3\pi+2\beta u-4\sqrt{\beta u\pi}}{4\alpha}$	$D^{G^*} = \frac{\pi-2\beta u}{2\beta}$	$\Omega^{G^*} = \frac{3\pi+2\beta u+4\sqrt{\beta u\pi}}{4}$
GB (NB solution)	$R^{N^*} = \frac{\pi+\beta u-2\sqrt{\beta u\pi}}{2\alpha}$	$D^{N^*} = \frac{\pi-2\beta u}{2\beta}$	$\Omega^{N^*} = \frac{2\pi+\beta u+2\sqrt{\beta u\pi}}{2}$
GB (optimal)			
for $4 < \frac{\pi}{\beta u} < 6 + 4\sqrt{2}$	$R^{O^*} = \varepsilon$	$D^{O^*} = \frac{\pi-2\beta u}{2\beta}$	$\Omega^{O^*} \approx \frac{3\pi+2\beta u}{2}$
for $\frac{\pi}{\beta u} > 6 + 4\sqrt{2}$	$R^{O^*} = \frac{\pi+2\beta u-4\sqrt{\beta u\pi}}{4\alpha}$	$D^{O^*} = \frac{\pi-2\beta u}{2\beta}$	$\Omega^{O^*} = \frac{5\pi+2\beta u+4\sqrt{\beta u\pi}}{4}$

Note: 1. Appropriation: appropriation without technology transfer.
2. License without GB: licensing contract without a grant-back clause.
3. GB (license fee): grant-back contract with a licensing fee.
4. GB (NB solution): grant-back contract with a Nash bargaining solution.
5. GB (optimal): grant-back contract with an optimal distribution.

Proposition 4. When the consumer surplus obtained from an improved final product is negligible, the ranking of social welfare is as follows:
(1) $\Omega^{O^*} > \Omega^{N^*} > \Omega^{A^*} > \Omega^{G^*} > \Omega^{J^*} > \Omega^{L^*}$ for $4 < \frac{\pi}{\beta u} < 6 + 4\sqrt{2}$; and
(2) $\Omega^{O^*} > \Omega^{N^*} > \Omega^{A^*} > \Omega^{J^*} > \Omega^{G^*} > \Omega^{L^*}$ for $\frac{\pi}{\beta u} > 6 + 4\sqrt{2}$.

Most of the ranking of social welfare is the same in Proposition 4 (1) and (2). The licensing contract with a grant-back clause (excluding the case of the grant-back contract with a licensing fee) leads to a higher level of social welfare than the other schemes. There are two reasons for this result. First, the grant-back contract mitigates the overincentive for follow-on innovation through the expectation of sharing it *ex-post facto*. Second, if they induce a more appropriate profit distribution between the firms, they reduce the overincentive for the initial innovation to a level much closer to the socially optimal level.

Meanwhile, the social welfare yielded by the grant-back contract with a licensing fee is quite low. It always generates higher profits than the contract without a grant-back cause. However, it significantly increases the attractiveness of winning competition in the initial innovation by allowing the licensor to extract all surplus from the licensee, so that the deterioration in the overincentive is the most serious. Consequently, it results in a lower level of social welfare than appropriation without technology transfer. [19]

Whereas the RJV achieves the optimal incentive for the initial innovation, it causes sizable common pool externalities on the follow-on innovation and decreases social welfare. This is because the uncertainty attached to the follow-on innovation requires the firms to conduct more investments to achieve the follow-on innovation. Since competition in the follow-on innovation never creates social welfare when the consumer surplus is negligible, it is a mere waste of research resources. Moreover, comparing the social welfare yielded by the RJV and the licensing contract without a grant-back clause, the former always provides a higher level of social welfare than the latter. Despite the same degree of competition observed in the follow-on innovation, the RJV saves more research resources allotted to the initial innovation.

These results are built on specific assumptions regarding the consumer surplus. If a significantly positive consumer surplus is incorporated into the model, the results can vary because a positive competition effect on the follow-on innovation would be, in turn, effectual. Section 4 highlights this aspect.

[19] For a relatively large basic revenue, π, it is lower than the RJV.

4 A significantly positive consumer surplus

Section 4 probes how the social welfare ranking is alternated by significantly positive consumer surplus. In such a case, competition in the follow-on innovation is of great importance since it can raise the probability of an improved final product emerging on the market.

We continue to suppose that firms cannot extract any consumer surplus into their profits. By assuming that social welfare (W) equals the sum of firms' profits (Ω) and expected consumer surplus ($\frac{D}{D+u}$ where $D = \sum_{n=1}^{2} D_n$), social welfare is redefined as:

$$W^X = \Omega^X + \frac{D^X C}{D^X + u}, \text{ with } X = J^*, A^*, L^*, G^*, N^*, \text{and } O^*, \text{ where } D^X = \sum_{n=1}^{2} D_n^X. \tag{15}$$

Equation (15) indicates that by separating consumer surplus from profits, profit maximization of the firms is not always consistent with social welfare maximization. This means that consumer surplus is solely attributable to consumers in the end, deriving from the unique benefit accruing to the use of the product. [20] Table 3 summarizes social welfare in each technological development scheme by focusing on $4 < \frac{\pi}{\beta u} < 6 + 4\sqrt{2}$. [21]

TABLE 2 Social welfare when the consumer surplus is positive

RJV	$W^{J^*} \approx \pi + \beta u + (1 - \frac{\beta u}{\pi})C$
Appropriation	$W^{A^*} = \frac{2\pi+\beta u+\sqrt{\beta u \pi}}{2} + (1 - \sqrt{\frac{\beta u}{\pi}})C$
License without GB	$W^{L^*} = \frac{\pi+\beta u+2\sqrt{\beta u \pi}}{2} + (1 - \frac{\beta u}{\pi})C$
GB (licensing fee)	$W^{G^*} = \frac{3\pi+2\beta u+4\sqrt{\beta u \pi}}{4} + (1 - \frac{2\beta u}{\pi})C$
GB (NB solution)	$W^{N^*} = \frac{2\pi+\beta u+2\sqrt{\beta u \pi}}{2} + (1 - \frac{2\beta u}{\pi})C$
GB (optimal)	$W^{O^*} \approx \frac{3\pi+2\beta u}{2} + (1 - \frac{2\beta u}{\pi})C$

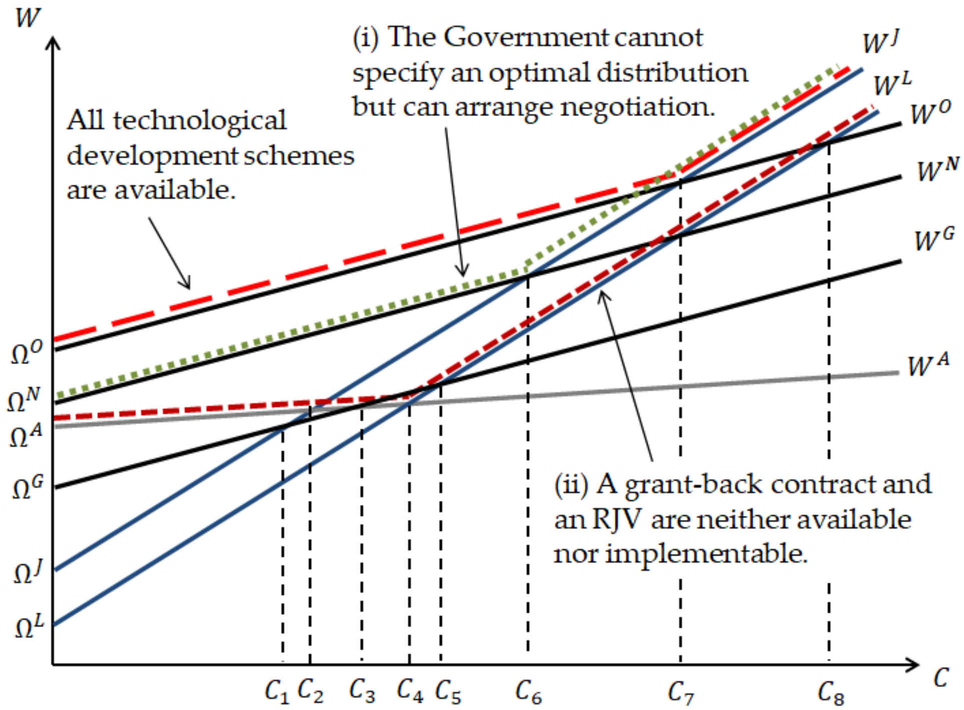
Note: 1. Appropriation: appropriation without technology transfer.
2. License without GB: licensing contract without a grant-back clause.
3. GB (licensing fee): grant-back contract with a licensing fee.
4. GB (NB solution): grant-back contract with a Nash bargaining solution.
5. GB (optimal): grant-back contract with an optimal distribution.

Figure 3 depicts social welfare along with the magnitude of consumer surplus. Obviously, the intercepts of the lines correspond to social welfare when consumer surplus (C) is zero, namely, only firms' profits (Ω^{X^*}). The slopes of the lines vary in each case; W^{J^*} and W^{L^*}

[20] Another assumption as a special case is that the elasticity of demand for an improved final product is exactly zero. This implies that a reduction in the price of a product increases demand but does not change the revenue of firms.

[21] The discussion in the case of $\frac{\pi}{\beta u} > 6 + 4\sqrt{2}$ is not any different from the following discussion and is omitted.

are the steepest, W^{A^*} is the flattest, and W^{G^*}, W^{N^*}, and W^{O^*} are intermediate. This slope of each line is consistent with the intensity of follow-on competition. More precisely, as the consumer surplus gets large, fiercer competition in the follow-on innovation increases social welfare through the higher probability of succeeding in that innovation. Proposition 5 briefly describes the observation from Figure 3.



$$C_1 = \frac{\pi(-\pi + 2\beta u + 4\sqrt{\beta u \pi})}{4\beta u} \qquad C_5 = \frac{\pi(2\pi + \beta u + 2\sqrt{\beta u \pi})}{4\beta u}$$

$$C_2 = \frac{\pi}{2} \qquad C_6 = \frac{\pi(2\sqrt{\beta u \pi} - \beta u)}{2\beta u}$$

$$C_3 = \frac{\pi\sqrt{\pi}}{4\sqrt{\beta u}} \qquad C_7 = \frac{\pi^2}{2\beta u}$$

$$C_4 = \frac{\pi\sqrt{\pi}}{2\sqrt{\beta u}} \qquad C_8 = \frac{\pi(2\pi + \beta u - 2\sqrt{\beta u \pi})}{2\beta u}$$

FIGURE 3 Diagram of social welfare

Proposition 5. Suppose a significantly positive consumer surplus. Then, we can derive the following points:

(1) If the consumer surplus is relatively small, the grant-back contract associated with an appropriate distribution is more socially desirable than an RJV or a licensing contract without a grant-back clause, and vice versa;

(2) If the consumer surplus is relatively large, the technological development schemes that firms choose may not induce the first-best level of social welfare; and

(3) The grant-back contract associated with an appropriate distribution is always more so-

cially desirable than appropriation without technology transfer, irrespective of the consumer surplus.

Proposition 5 points to the importance of making various technological development schemes both available and implementable.

For example, consider the grant-back contract with an optimal distribution and the RJV. Proposition 5 (1) states that when the consumer surplus is relatively small as $C < C_7$, we obtain $W^{O^*} > W^{J^*}$. Then, it is imperative not only to have a grant-back contract scheme made available to firms, but to also implement an optimal profit distribution to definitively reduce overinvestment in the initial innovation. Furthermore, the firms are likely to choose a technological development scheme from the perspective of profit maximization (Ω^{O^*}), which is consistent with the maximization of social welfare (W^{O^*}).

Conversely, as Proposition 5 (2) asserts, if the consumer surplus is relatively large as $C > C_7$, we obtain $W^{J^*} > W^{O^*}$. Nevertheless, the firms still prefer the grant-back contract scheme to the RJV, not taking into account the consumer surplus, because their decisions will be made based solely on the ranking of Ω^{X^*}. To achieve the maximum social welfare in the aforementioned case, it is necessary to form an RJV that establishes a strong competition effect in the follow-on innovation. Since there is an apparent discrepancy between profit and social welfare, we may as well entrust the government to encourage firms to put and RJV in practice. In this sense, when firms do not consider the consumer surplus, it may be possible to justify policy intervention into technological development schemes to form an RJV.

With regard to Proposition 5 (3), even if any magnitude of the consumer surplus is assumed, $W^{O^*} > W^{N^*} > W^{A^*}$ is always preserved. Although appropriating the initial technology minimizes the cost of technological development in the follow-on innovation, its positive effect is, regardless of the consumer surplus, less than the benefit from the grant-back schemes associated with an appropriate distribution. This result is not surprising, since we have already derived $V^{O^*} > V^{N^*} > V^{A^*}$, and the positive competition effect of a grant-back contract is necessarily greater than appropriation without technology transfer.

In conclusion, while existing studies have not considered innovation features such as the consumer surplus separated from profit in their welfare analyses, by simply assuming that social welfare is regarded as firms' profits, our analysis sheds new light on the aspects of choosing a technological development scheme in accordance with the consumer surplus.

Supplementary note

We have assumed that all technological development schemes are both available to firms and implementable for the government. But suppose that (i) a government is unable to specify an optimal distribution in the grant-back contract; and (ii) the grant-back clause and RJV are unavailable and unimplementable due to institutional and legal inadequacies or costly arrangements. [22]

With regard to (i) and (ii), when the consumer surplus is so negligible that $C < C_6$ ($C < C_4$), the grant-back contract with a Nash bargaining solution (appropriation without technology transfer) is more socially desirable than the RJV (the licensing contract without a grant-back clause). In contrast, if the consumer surplus is large enough that $C > C_6$ ($C > C_4$), then technological competition in the follow-on innovation has a positive effect on social welfare. Figure 3 illustrates the highest level of social welfare along with the consumer surplus.

5 Conclusion

In this study, we have investigated which technological development scheme is most desirable for technological competition and cumulative innovation. We demonstrated that when the consumer surplus is negligible, there is a trade-off between investments in the initial and follow-on innovations. We also found that a grant-back contract with an appropriate profit distribution mitigates the social overincentive for both the initial and follow-on innovations. This result is due to the fact that such a grant-back contract not only decreases the overincentive for the follow-on innovation by ensuring the licensor access to the follow-on innovation, but also reduces the overincentive for the initial innovation by appropriately controlling the attractiveness of achieving the initial innovation. In particular, we demonstrated that if a government can specify a particular distribution, a socially optimal investment in the initial innovation can be realized. Furthermore, assuming a significantly positive consumer surplus instead, we revealed that competition in the follow-on innovation creates a higher level of social welfare as the consumer surplus is large. This implies that the positive competition effect may overcome the overincentive problem, that is, the common pool externalities.

We can derive from this study the implication that policymakers need to encourage firms to deliberately employ an appropriate technological development scheme, taking into account various factors such as the cost of technological development, the degree of uncertainty, and the consumer surplus. Thus, this paper makes its greatest contribution to the literature on patent practices and innovation by uncovering the imperative government role of exercising a so-called compulsory licensing system to mitigate common pool externalities, especially that of the initial innovation.

What follows should be discussed as future challenges. First and foremost, the model structure should be improved to endogenize firms' decisions to spontaneously choose an appropriate technological development scheme after the initial innovation, in particular, whether a grant-back clause is included in the licensing contract or not. Additionally, interventions of the government should be strictly defined to motivate firms to implement a

[22] When $1 < \frac{\pi}{\beta u} < 4$ holds, firms cannot apply a grant-back clause due to the relatively high cost and high level of uncertainty of developing technology D.

particular licensing contract. Second, the uncertainty factor should also be included in the initial innovation, although this paper has not conducted a full analysis due to the extreme complexity of the analytical model. Then, increased investment in the initial innovation may be justified on the grounds that it can sow the seeds of achieving cumulative innovation. Finally, it would be critical to examine how incentives can be more closely connected to social welfare when firms' extraction of the consumer surplus is, at least, partially possible.

Appendix

The mathematical proofs of the propositions and lemmas are gathered here.

Lemma 1. (1) $R^{A^*} - R^{J^*} = \frac{2\pi+\beta u-3\sqrt{\beta u\pi}}{2\alpha} - \varepsilon \simeq \frac{(\sqrt{\pi}-\sqrt{\beta u})^2+\sqrt{\pi}(\sqrt{\pi}-\sqrt{\beta u})}{2\alpha} > 0 \Leftrightarrow R^{A^*} > R^{J^*}$ under $\frac{\pi}{\beta u} > 1$. (2) $D^{J^*} - D^{A^*} = (\frac{\pi-\beta u}{\beta}) - (\sqrt{\frac{u\pi}{\beta}} - u) = \sqrt{\frac{\pi}{\beta}}(\frac{\sqrt{\pi}-\sqrt{\beta u}}{\sqrt{\beta}}) > 0 \Leftrightarrow D^{J^*} > D^{A^*}$ under $\frac{\pi}{\beta u} > 1$. ■

Lemma 2. (1) $R^{A^*} - R^{L^*} = \frac{2\pi+\beta u-3\sqrt{\beta u\pi}}{2\alpha} - \frac{\pi+\beta u-2\sqrt{\beta u\pi}}{2\alpha} = \frac{\sqrt{\pi}(\sqrt{\pi}-\sqrt{\beta u})}{2\alpha} > 0 \Leftrightarrow R^{A^*} > R^{L^*}$ under $\frac{\pi}{\beta u} > 1$. (2) $D^{L^*} - D^{A^*} = \frac{\pi-\beta u}{\beta} - (\sqrt{\frac{u\pi}{\beta}} - u) = \frac{\sqrt{\pi}(\sqrt{\pi}-\sqrt{\beta u})}{\beta} > 0 \Leftrightarrow D^{L^*} > D^{A^*}$ under $\frac{\pi}{\beta u} > 1$. ■

Proposition 1. We compare R^{G^*} to R^{A^*} and R^{L^*} for $\frac{\pi}{\beta u} > 4$. $R^{A^*} - R^{G^*} = \frac{2\pi+\beta u-3\sqrt{\beta u\pi}}{2\alpha} - \frac{3\pi+2\beta u-4\sqrt{\beta u\pi}}{4\alpha} = \frac{\pi-2\sqrt{\beta u\pi}}{4\alpha} = \frac{\sqrt{\pi}(\sqrt{\pi}-2\sqrt{\beta u})}{4\alpha} > 0 \Leftrightarrow R^{A^*} > R^{G^*}$. $R^{G^*} - R^{L^*} = \frac{3\pi+2\beta u-4\sqrt{\beta u\pi}}{4\alpha} - \frac{\pi+\beta u-2\sqrt{\beta u\pi}}{2\alpha} = \frac{\sqrt{\pi}(\sqrt{\pi}-2\sqrt{\beta u})}{4\alpha} > 0 \Leftrightarrow R^{G^*} > R^{L^*}$. We can therefore conclude that $R^{A^*} > R^{G^*} > R^{L^*} > R^{J^*}$. Next, we compare D^{G^*} to D^{A^*} and $D^{L^*}(= D^{J^*})$. $D^{G^*} - D^{A^*} = \frac{\pi-2\beta u}{2\beta} - (\sqrt{\frac{u\pi}{\beta}} - u) = \frac{\sqrt{\pi}(\sqrt{\pi}-2\sqrt{\beta u})}{2\beta} > 0 \Leftrightarrow D^{G^*} > D^{A^*}$. $D^{L^*} - D^{G^*} = \frac{\pi-\beta u}{\beta} - \frac{\pi-2\beta u}{2\beta} = \frac{\pi}{2\beta} > 0 \Leftrightarrow D^{L^*} > D^{G^*}$. These results yield $D^{L^*} = D^{J^*} > D^{G^*} > D^{A^*}$. ■

Proposition 2. See the main text. ■

Proposition 3. (1) By solving $R^{O^*}(k^*) = 0$ with regard to k, we obtain $k^* = \frac{-\pi-2\beta u+4\sqrt{\beta u\pi}}{2\pi}$. Next, consider the equation, $-\pi - 2\beta u + 4\sqrt{\beta u\pi} = 0$, which can be transformed into $f(\sqrt{\frac{\pi}{\beta u}}) = -(\sqrt{\frac{\pi}{\beta u}})^2 + 4(\sqrt{\frac{\pi}{\beta u}}) - 2 = 0$ by dividing the both sides of the equation by βu. Solving this quadratic equation yields $\sqrt{\frac{\pi}{\beta u}} = 2 \pm \sqrt{2}$, namely $\frac{\pi}{\beta u} = 6 + 4\sqrt{2}$ ($\simeq 11.657$) or $6 - 4\sqrt{2}$ ($\simeq 0.343$). Therefore, $f(\sqrt{\frac{\pi}{\beta u}}) > 0$ for $6 - 4\sqrt{2} < \frac{\pi}{\beta u} < 6 + 4\sqrt{2}$. However, since $\frac{\pi}{\beta u} > 4$ is assumed in the grant-back case, $f(\sqrt{\frac{\pi}{\beta u}}) > 0$ only for $4 < \frac{\pi}{\beta u} < 6 + 4\sqrt{2}$. Assuming $4 < \frac{\pi}{\beta u} < 6 + 4\sqrt{2}$, we find a unique $k^* = \frac{-\pi-2\beta u+4\sqrt{\beta u\pi}}{2\pi} > 0$ that induces $R^{O^*}(k^*) = 0$ because $R^{O^*}(0) < 0$ and $R^{O^*}(1) > 0$

(i.e., the intermediate-value theorem). If an approximate specification is given as $k^{O^*} \approx k^*$, the optimal investment in technology R, such as $R^{J^*} = \varepsilon > 0$, can be achieved. (2) We can demonstrate $k^* < \frac{1}{2}$ since $\frac{1}{2} - k^* = \frac{\pi+\beta u-2\sqrt{\beta u\pi}}{\pi} = \frac{(\sqrt{\pi}-\sqrt{\beta u})^2}{\pi} > 0$. ■

Proposition 4. (1) When $4 < \frac{\pi}{\beta u} < 6 + 4\sqrt{2}$, social welfare in each case can be derived as follows: $\Omega^{J^*} \simeq \pi + \beta u$; $\Omega^{A^*} = \frac{2\pi+\beta u+\sqrt{\beta u\pi}}{2}$; $\Omega^{L^*} = \frac{\pi+\beta u+2\sqrt{\beta u\pi}}{2}$; $\Omega^{G^*} = \frac{3\pi+2\beta u+4\sqrt{\beta u\pi}}{4}$; $\Omega^{N^*} = \frac{2\pi+\beta u+2\sqrt{\beta u\pi}}{2}$; and $\Omega^{O^*} \simeq \frac{3\pi+2\beta u}{2}$. Then, we obtain: $\Omega^{O^*} - \Omega^{N^*} = \frac{(\sqrt{\pi}-\sqrt{\beta u})^2}{2} > 0 \Leftrightarrow \Omega^{O^*} > \Omega^{N^*}$; $\Omega^{N^*} - \Omega^{A^*} = \frac{\sqrt{\beta u\pi}}{2} > 0 \Leftrightarrow \Omega^{N^*} > \Omega^{A^*}$; $\Omega^{A^*} - \Omega^{G^*} = \frac{\sqrt{\pi}(\sqrt{\pi}-2\sqrt{\beta u})}{4} > 0 \Leftrightarrow \Omega^{A^*} > \Omega^{G^*}$; $\Omega^{G^*} - \Omega^{J^*} = \frac{-\pi-2\beta u+4\sqrt{\beta u\pi}}{4} > 0 \Leftrightarrow \Omega^{G^*} > \Omega^{J^*}$; and $\Omega^{J^*} - \Omega^{L^*} = \frac{(\sqrt{\pi}-\sqrt{\beta u})^2}{2} > 0 \Leftrightarrow \Omega^{J^*} > \Omega^{L^*}$ under this condition. Therefore, $\Omega^{O^*} > \Omega^{N^*} > \Omega^{A^*} > \Omega^{G^*} > \Omega^{J^*} > \Omega^{L^*}$. (2) When $\frac{\pi}{\beta u} > 6+4\sqrt{2}$, the social welfare of an optimal grant-back contract changes to $\Omega^{O^*} = \frac{5\pi+2\beta u+4\sqrt{\beta u\pi}}{4}$. Comparing Ω^{O^*} and Ω^{N^*} results in $\Omega^{O^*} - \Omega^{N^*} = \frac{\pi}{4} > 0 \Leftrightarrow \Omega^{O^*} > \Omega^{N^*}$. In addition, $\Omega^{A^*} - \Omega^{J^*} = \frac{\sqrt{\beta u}(\sqrt{\pi}-\sqrt{\beta u})}{2} > 0 \Leftrightarrow \Omega^{A^*} > \Omega^{J^*}$; $\Omega^{J^*} - \Omega^{G^*} = \frac{\pi+2\beta u-4\sqrt{\beta u\pi}}{4} > 0 \Leftrightarrow \Omega^{J^*} > \Omega^{G^*}$; and $\Omega^{G^*} - \Omega^{L^*} = \frac{\pi}{4} > 0 \Leftrightarrow \Omega^{G^*} > \Omega^{L^*}$. Therefore, $\Omega^{O^*} > \Omega^{N^*} > \Omega^{A^*} > \Omega^{J^*} > \Omega^{G^*} > \Omega^{L^*}$. ■

Proposition 5. See the main text. ■

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