Standard setting, compatibility externalities and R&D

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Abstract

This paper considers a R&D contest between two firms who can choose to concentrate their research in one of two avenues or approaches. In the R&D contest, firms compete in two stages. In the first stage, firms choose which approach they will investigate, after which they endogenously select optimal effort level given firms' choice of approach in the second stage. There are "compatibility externalities" if they choose the same approach. However, there is also greater probability of simultaneous discovery which may cause harmful results to both firms. We examine 3 situations with different payoff structures by considering the Bertrand R&D game, the equal sharing R&D game and the research alliance game. The equilibrium avenue choice in each game depends on the size of compatibility externality and it may exhibit too much differentiation or too much duplication. The equilibrium effort choice conditional on duplication is inefficient except in the Bertrand R&D game, while the equilibrium effort choice is efficient when firms choose different research avenues. The result of the excess differentiation and the efficient investment choice in the Bertrand R&D game suggest that the lump-sum investment subsidy may need to be implemented in the US wireless mobile phone industry to reduce inefficiency involved in excess differentiation without distorting efficient investment choice.

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1 Introduction

Many products have value only when the products are used in combination with other products. For example, in order to watch DVD, one needs a DVD player, ATM cards are useless without automatic teller machines. A cell phone by itself is of no use in the area where carrier's service is not provided. These are examples of products which need complementary goods in generating their values and they are described as forming "systems".[1] In such systems markets, compatibility or standardization among systems is of importance to consumers. Consumers may enjoy more benefits by purchasing goods from compatible systems than from an isolated incompatible system[2]. Especially in the presence of network externality in consumption of compatible goods, consumers may put higher value on products which are compatible across systems since compatibility increases the actual network size of each system to that of entire interconnected systems.[3]

However, whether compatibility is beneficial to firms is less clear. Some of benefits that consumers enjoy thanks to compatibility may be exploited by firms. Then, the consumers' compatibility benefits eventually feed back into firms' incentive to make their product compatible.[4] Firms can also benefit directly from compatibility. If the products are compatible, then economies of scale may occur in the production process of the parts used in compatible products, resulting in lower prices of inputs. In some occasions, firms may enhance quality of their products or lower their production costs by sharing their compatible facilities.[5] When such benefits from compatibility is

[1]Katz & Shapiro(1994) define a system as a collection of two or more components together with an interface that allows the components to work together.

[2]If standardization reduces variety and consumers place much value on variety, welfare effect of standardization on consumers may be unclear. For the explicit analysis on tradeoff between efficiency and variety, see Farrell and Saloner (1986).

[3]Farrell & Saloner (1985) identify in detail benefits from compatibility or standardization occurring to consumers that include, but not restricted to : a market-mediated effect, as when a complementary good becomes cheaper and more readily available the greater the size of compatible systems ; a thicker second-hand(used) market, enhanced price competition among firms.

[4]We use compatibility benefit and network benefit interchangeably. Similarly, compatibility externality and network externality are used interchangeable in the rest of the paper.

[5]The wireless communication service industry offers one good example. AT&T, Cingular and T-Mobile which adopt the same GSM technology, can share their networks in providing their service to customers. By doing so, they may construct the interconnected

greater, firms has more incentive to choose a same standard, in which they compete within a standard. But, compatibility may bring about losses to firms, too. When products are compatible, consumers may not incur any switching cost in purchasing other compatible products, which may make competition within a standard very fierce[6]. In contrast, if products are incompatible and are considered to have different characteristics, then firms compete only for some fraction of the market which consists of consumers who are not in the installed base of any standard.[7] In such cases where price competition is dampened by firms' choosing different standards, firms may prefer incompatibility, in which they compete with their own standards.

Foreseeing such situations in the product market, firms at the pre-R&D stage can choose between competition within a standard and competition with its own standard. Then, firms in such situations have a following trade-off. Seeking compatibility by engaging in R&D on the research avenue for similar compatible products, may yield greater rewards given an exclusive success in R&D, as long as the greater network benefits can be eventually captured by firms. But, on the other hand, it also entails the possibility that the R&D race may end up with simultaneous discovery, resulting in losses to all the firms who made discovery simultaneously.[8] How simultaneous discovery dissipates the rewards from R&D success may depend on how

national GSM network so that each firm with incomplete network only, can provide seamless connection in any areas wherever some other GSM carrier has networks. This is the typical example of "physical" network externality(Oz, 2001).

[6]Even when products are almost compatible, firms often create artificial switching costs to build an installed base. For example, wireless telecommunication companies often charges a penalty fee to customers who discontinue the service before the contract expires. In such cases, the penalty fee which customers have to incur will be the switching cost. Mileage or points program used in many industries is another good example of artificial switching cost.

[7]If different incompatible products don't provide its intrinsic values, so consumers consider the products as just incompatible but almost identical, one standard may eventually win all the market, which is often called as "tipping". Since tipping occurs in favor of a firm with more installed base, competition for installed base is very fierce in the industries where tipping occurs. For examples of the industries where "tipping" have been observed, see Katz & Shapiro(1994).

[8]If there are several technologies possible for a standard and network benefits is large enough to outweigh the loss resulting from competition within a standard no matter which technology is standardized, then all the firms would always prefer compatibility to incompatibility. In that case, choice between compatibility vs incompatibility wouldn't be an issue any more. Instead a new issue would arise : which standard is chosen in equilibria and which standard is socially efficient? See Farrell & Saloner(1985) for more in detail.

competitive the relevant industry is.

First consider the case in which all the rewards from R&D success are competed away when simultaneous discovery occurs. One good example in such extreme case can be found in the airplane manufacturer industry. In the 1960s, Douglas and Lockheed introduced the Douglas DC-10 and the Lockheed L-1011 respectively within months of each other. Both of them being the similar wide-bodied three-engined jet airliners, both Douglas and Lockheed made great losses from the simultaneous discovery (The Economist(1985)). Such an extreme case where all the rewards from R&D success are bid away in the case of simultaneous discovery can be captured by the "Bertrand payoff" structure (winner-take-all and no reward in the event of simultaneous discovery). Second, in some industries where competition doesn't dissipate the R&D rewards completely, firms often split the rewards from R&D success when simultaneous discovery occurs. For example, Sega and Nintendo, the two dominant providers in the video game market, have split the market since the development of their own standards. Third, in some industries, firms form a certain type of research alliances through which they cooperate in creating compatibility benefit by agreeing on the same standard or in reducing competition by agreeing on sharing each other's technologies.[9] Consider the example of the anti-ulcer drug market in Australia where Tagamat developed by Smith Kline and Zantac developed by Glaxo were the two dominant brands in early 1980's. Smith Kline and Glaxo have had a joint-patent on Tagamat and Zantac, by which they agreed not to sue the other for breach of prior patent when they engaged in their R&D independently. With such a joint-patent, Smith Kline and Glaxo could reap externality from each other's technologies without causing intense competition. In all the cases mentioned above, simultaneous discovery reduces the reward from R&D success, thereby giving firms the incentive to engage in R&D on different incompatible systems(or different products).[10] If the prospect products from different incompatible research avenues have their own intrinsic values, then simultaneous successes in different R&D avenues(or R&D sites) will not impair each other's payoffs.[11] How much investments firms make is also af-

[9] There are various forms of research alliance each of which has different contents of cooperation. If they agree to share all the R&D rewards, then it is no different from a merged firm, while firms cooperate to a very limited extent, exchange of some information

[10] Even when firms form a research alliance, it is clear that a firm would be better off with an exclusive discovery.

[11] The research avenues are referred to as "site" following the analogy in the "the buried

fected by the possibility of simultaneous discovery because firms may have less incentive for investment as simultaneous discovery dissipates more of the reward from R&D success. Hence, given that such negative effect on firms' payoffs of simultaneous discovery may result in distortion in firms' incentive structure for optimal site choice and optimal investment choice, we might have the following questions : do firms seek compatibility and herd on the same type of R&D avenues in the expectation of capturing compatibility benefits or compatibility externalities? Or, do firms seek incompatibility and diversify their research fearing simultaneous discovery? Are firms' noncooperative R&D choices socially efficient? Are firms' R&D intensities given site choice efficient? If not, what kind of intervention may improve the social welfare? Which standard regime would work between the mandatory single standard regime and the multiple standard regime? [12]

In the theoretical literature on standards and network externality, the focus has been mainly on adoption of new products, not on how new technologies come into existence in the first place : the R&D avenue choice. We provide a simple static R&D model in which two firms compete in R&D race in two stages for new generation technologies where two different R&D avenues are available, each being for different technologies incompatible with each other. In the first stage, firms sequentially choose which site to investigate. In the second stage, observing the result of the site choice, firms choose its optimal probability of success(or effort) given site choice.[13] When firms duplicate R&D avenue choice, the reward from an exclusive success is bigger than the reward from R&D success when firms differentiate in the research avenue choice. But if firms duplicate in the research avenue choice, firms bear the risk of simultaneous discovery, which might result in losses to both firms. Firms can choose to differentiate their research avenue choice and avoid the possibility of simultaneous discovery even though the rewards from R&D is smaller than the rewards from an exclusive R&D success given duplication in research avenue choice. In order to capture various results of simultaneous discovery, we consider 3 different noncooperative games each of which captures the 3 different situations mentioned earlier : **the Bertrand R&D**

treasure problem". Hereafter, we use both terms interchangeably.

[12] We assume that the simultaneous discovery in different sites doesn't dissipate the reward from R&D success by either firm, which is discussed in more detail in 2.2.1. Hereafter, simultaneous discovery means simultaneous discovery on the same site unless specified.

[13] Hereafter, we use effort and probability of success in R&D interchangeably. The reason for that is discussed later in 2.1.

game where simultaneous discovery on the same site results in dissipation of all the rewards from R&D success, **the equal sharing R&D game** in which each firm gets a half of the R&D rewards in the event of simultaneous discovery, and **the research alliance game** in which firms may choose to investigate the same site by forming a research alliance in which firms independently investigate, but at the same time cooperate in a way that they share some of the R&D rewards conditional on R&D success.

The results we obtain are as follows.

First, in the Bertrand R&D game, the equilibrium effort level or investment conditional on site choice is efficient both when firms choose different sites(differentiation) and when firms choose the same site(duplication). Such efficiency outcome results from the coincidence between the private incentive for increase in effort and that of the social planner : a firm has less incentive for duplication in proportion to the more effort exerted by its rival firm since the increase in the rival firm's effort raises the probability of simultaneous discovery, thereby reducing the expected payoff from R&D. In the social optimum, as one firm's probability of success in R&D is higher, the marginal contribution of the other firm's effort is less, so the increase in one firm's effort should be accompanied by the decrease in the other firm's effort in the social optimum. But, the equilibrium site choice may exhibit too much differentiation for certain set of value of compatibility externality since when it chooses a different site, firms don't consider the network benefits which would occur to the rival firm in choosing the same site.

Second, in the equal sharing R&D game, firms equilibrium effort level conditional on duplication is inefficiently high since firms receive the reward for its second discovery which doesn't add the social welfare. Such excessive incentive for effort also causes firms to choose the same site too much when compatibility externality has intermediate value, resulting in excess duplication.

Third, in the research alliance game where firms share some of the rewards given R&D success, firms don't consider the benefit on the rival firm of its own investment which dilutes incentive for increase in investment, thereby resulting in insufficient investment in equilibrium effort choice. But, due to the payoff structure in which firms receive rewards for its second discovery as in the equal sharing R&D game, firms also have excessive incentive for investment. The interplay of such conflicting incentives result in non-monotonic inefficiency in equilibrium effort choice. Also it turns out that the excessive incentive for investment outweighs the insufficient incentive for investment when compatibility externality is low enough, which results in excess duplication in site choice.

Fourth, the optimal policy mix to reduce inefficiencies involved in site choice and effort choice depends on the size of compatibility externality. Without sufficient information on the size of compatibility externality, choosing a mandatory single standard bears risk of loss in additional innovation, lowering the social welfare. However, if the prospect product market is expected to be very competitive so that the relevant industry is close to the case of Bertrand R&D game, then there may occur excess differentiation in site choice in the multiple standard regime, which suggests that the lump-sum investment subsidy may need to be implemented in the US wireless mobile phone industry to reduce inefficiency involved in excess differentiation without distorting efficient investment choice.

As mentioned earlier, the existing theoretical literature in economics on standards and network externality, has mainly focused on the issues regarding introduction of new products which are developed already.

Farrell and Saloner(1985) analyze the sources of inefficiency inherent in standardization where firms choose between incompatible standards in a dynamic setting. They find that excess inertia may occur due to the failure of coordination among firms adopting a new superior standard when information on firm's preferences on standards is incomplete.

Katz and Shapiro(1985) analyze network externality effects under oligopolistic competition on market equilibrium. In their model, consumers' foresight on the potential size of the networks, determine effective networks. Since the rationality restriction on the expectations of consumers allow many sets of expectations in the equilibria, there exist multiple fulfilled expectations equilibria. In their analysis of the firms' incentives to produce compatible goods, they find that firms with good reputations or large existing networks tend to be against compatibility while firms with weak reputation or small existing networks tend to favor compatibility.

Farrell and Saloner(1988) discuss a coordination problem in a finite period model in which firms with different preferences on technologies, seek to agree on one technology. The payoff structure in their model is as follows : a firm is best off if all the firms agree on the technology which it prefers. But, a firm would rather agree on the technology less preferred by it than be incompatible. This payoff structure allows Farrell and Saloner to ignore the case where incompatibility may arise in equilibria. Then, firms play a battle of sexes game each period. In their model, Farrell and Saloner examine three different coordination process: the committee as a pre-play communication mechanism, the market or bandwagon process and a hybrid mechanism in which firms use both bandwagon and committee strategies. They obtain the result that the committee unambiguously outperforms the bandwagon system and the hybrid game gives strictly greater payoffs than the pure committee system.

Katz and Shapiro (1992) consider a market with network externalities where an incumbent with existing installed base competes with an entrant with lower costs but having the disadvantage of no installed base. In their dynamic model, with the crucial assumption of exponential growth of market, they analyze the situation that incumbent's advantage of installed base may not be important when compared to "future" installed base. In those situations, consumers' expectations play a critical role and many fulfilled expectations equilibria exist, one of which involves "insufficient friction". They show that an entrant has the incentive to seek incompatibility unilaterally if licensing contracts as side-payment system is not perfect.

Even though Katz and Shapiro(1985, 1992) identify some of firms' incentives to seek compatibility or incompatibility, they don't capture firms' motives to seek incompatibility fearing simultaneous discovery since all the products in their models are already developed and no R&D issue arises. Also, in their model, firms have conflicting incentives for compatibility, which are determined by asymmetry in position in market structure. Firms with larger installed base favor incompatibility while firms with smaller installed base favor compatibility. In our model, symmetric firms have the same preference toward compatibility where the preference toward compatibility is determined by conflicting forces : compatibility externality and simultaneous discovery.

Among few attempts to thoroughly discuss the effect of compatibility externality or network benefits on the R&D competition, Kristiansen(1998)is noteworthy. Kristiansen(1998) analyzes the situation in which two firms engage in R&D race in a dynamic setting where introducing technology earlier incurs more costs. He finds that firms' incentive to win over installed base brings firms to play the game of prisoners' dilemma so that the firms may introduce new incompatible technologies in the equilibrium earlier than in the Pareto Optimum. His model differs from our model in many ways as follows. First, the concept of "R&D site" isn't explicitly considered in Kristiansen's model. So firms' competition in site choice can't be captured in his model, while it is one of the main issues in our model. Second, in his model the new technologies developed by each firm is assumed to be incompatible with each other in the basic model. Hence, compatibility isn't a choice in his model, while compatibility choice is one of firms' main strategies in our model. Third, he considers standard agreement and compulsory licensing to avoid excessive differentiation. This is essentially discussing the "social planner's optimum" in our model. In his model, the social optimum cannot arise from a non-cooperative game. In our model, it sometimes can. Fourth, in his model, the stand-alone value of the product developed from R&D is realized from an *ex ante* identical distribution function across firms with no mass in it. Since a firm with higher stand-alone value wins the R&D race, the situation close to simultaneous discovery in our model may occur only when the two firms' stand-alone value is identical, which occurs with zero probability in his model. Hence the problem of simultaneous discovery that is our main issue can't be captured in his model. Fifth, there is no R&D in his model in a strict sense since there is no probability of failure in R&D in Kristiansen's model.

Another paper which is close to our paper is Chatterjee and Evans (2003). They analyze firms' R&D avenue or site choice problem in a dynamic setting where there's only one right site with the prize buried in it. As in our model, they incorporate the case of simultaneous discovery into their discrete time model. Even though firms prefer to avoid simultaneous discovery, herding on the more promising project may occur in equilibria since there's only one right site. Also, they analyze firms' strategic incentives to induce the rival to choose the different site through influencing the rival's belief on the probabilities of each site's being the right one. The main difference between our model and their model is that, in their model, the projects are perfectly correlated. Since there is only one right project, if the belief on one site's being the right one, increases, then, the belief on the other site's being the right one, decreases. In our model, the treasures are buried with probability one in both sites. Another difference is that they don't model network or compatibility benefit which is the main source of incentive for firms to seek duplication in R&D avenue choice in our model. In their model, if firms duplicate on a particular site, then that's because the probability of the prize being buried in that project is high enough to offset more than the expected loss caused by possible simultaneous discovery. The last big difference is that they only consider the Bertrand R&D game, while we consider the equal sharing R&D game and the research alliance game as well so that we may derive a policy implication on standard setting.

2 Model

2.1 Description of model

There are two "sites" or research avenues on technologies, S_1 and S_2, available to the two symmetric firms, A and B. One may consider the sites as research paths in which firms engage in R&D for the new generation of technology.[14] Let S_A be the site chosen by the firm A and S_B by the firm B. For simplicity, assume that the reward from R&D success is not site-specific. Let $V(n)$ represent the reward from R&D success with n being the number of the firm(s) choosing the same site. Denote by (S_l, S_k) with $S_l, S_k \in \{S_1, S_2\}$ the profile of firms' site choice where the firm A and the firm B choose the site S_l and the site S_k respectively. Denote by $V_i(S_l, S_k)$ the firm i's expected revenue from R&D when the firms' site choice is (S_l, S_k). There occurs *compatibility externality* in firms' reward from R&D success when firms choose the same site, which implies $V(2) > V(1)$. Firms incur the R&D activity cost, c of which level is endogenously chosen by firms. In each site, a firm succeeds in R&D activity with π, the probability of success which depends on the level of c, the R&D activity cost. We call π, the probability of success as "effort" since π captures general characteristics of effort in the sense that raising π increases the expected value of R&D activity, but it costs to raise π. Then, specifically we assume that π has an one-to-one functional relation with c that the cost of obtaining π is $c(\pi)$ where $c(\pi)$ is assumed to be strictly convex and smooth.

Firms move in two stages : In the first stage, firms sequentially choose sites to investigate. In the second stage, after observing each other's site choice, firms simultaneously choose the level of R&D activity cost to determine the optimal effort level(hence the probability), after which they engage in R&D.

Note that firms' different site choices in the first stage are followed by the corresponding different subgames in the second stage where firms solve the following the optimal effort choice problem,

$$\max_{\pi_i}\{V_i(S_i, S_j) - c_i(\pi_i)\} \text{ for given } (S_i, S_j)$$

[14] We define a "site" in a broad sense that several slightly different research projects may be available in each site. With such interpretation, the model can capture the case that even when each project is well protected under a patent, the fundamental technologies, i.e., the "site" which the projects are based on, is not protected but available to all firms without any legal restriction. For another aspect in definition of the site, see 2.2.1.

where $i, j \in \{A, B\}$ with $i \neq j$. Then, foreseeing optimal effort choices in each subgame, firms can figure out what its optimal site is by using typical backward induction in solving the following optimal site choice problem,

$$\max_{S_i \in \{S_1, S_2\}} \{V_i(S_i, S_j^*) - c_i\}$$

where S_j^* is the site chosen by the firm j in the equilibrium. Then, the profile of each firm's choice of the optimal site and effort level, $((S_A^*, \pi_A^*), (S_B^*, \pi_B^*))$ constitutes the subgame perfect Nash equilibrium in the game.

We consider 3 different kinds of games in the main section : the Bertrand R&D game, the equal Sharing R&D game, and the research alliance R&D game. The 3 games differ in the expected revenue from R&D success when duplication in site choice is followed by simultaneous discovery, resulting in different $V_i(S_i, S_j)$ for $i \in \{A, B\}$ with $S_i = S_j$. For example, suppose both firms choose the site S_1. Then, in the Bertrand R&D game, the firm i's expected revenue from R&D success conditional on both firms being on S_1, is

$$V_i(S_1, S_1) = \pi_i^S (1 - \pi_j^S) V(2),$$

where π_i^S is the firm i's effort level conditional on both firms being on the same site. In the equal sharing R&D game,

$$V_i(S_1, S_1) = [\frac{1}{2}\pi_i^S \pi_j^S + \pi_i^S (1 - \pi_j^S)] V(2).$$

In the research alliance game where firms share the extra R&D reward from compatibility externality by forming a research alliance, the first mover, the firm A's expected revenue from R&D is

$$\begin{aligned} V_A(S_1, S_1) &= [\pi_A(1 - \pi_B) + \frac{1}{2}\pi_A \pi_B] V(1) + \\ &\quad \frac{1+\lambda}{2}[\pi_A(1 - \pi_B) + \pi_B(1 - \pi_A) + \pi_A \pi_B][V(2) - V(1)] \\ &= \frac{1}{2}\pi_A(2 - \pi_B) + \frac{1+\lambda}{2}(\pi_A + \pi_B - \pi_A \pi_B)[V(2) - 1] \end{aligned}$$

while the second mover B's expected revenue from R&D is

$$\begin{aligned} V_B(S_1, S_1) &= [\pi_B(1 - \pi_A) + \frac{1}{2}\pi_B \pi_A] V(1) + \\ &\quad \frac{1-\lambda}{2}[\pi_A(1 - \pi_B) + \pi_B(1 - \pi_A) + \pi_A \pi_B][V(2) - V(1)] \\ &= \frac{1}{2}\pi_B(2 - \pi_A) + \frac{1-\lambda}{2}(\pi_A + \pi_B - \pi_A \pi_B)[V(2) - 1] \end{aligned}$$

where the λ is the parameter representing sharing proportion.[15]

2.2 Discussion of model

2.2.1 Independency between the different sites in R&D rewards

We assume that the rewards from R&D success in different sites are independent in the sense that simultaneous discovery in different sites doesn't affect the value of R&D success in each site.[16] The assumption relates to how we define the "site". We define the site such that the products developed from the different sites have their intrinsic values targeted for groups of consumers with differentiated preferences. Then, each discovery captures different segments of the market so that simultaneous discovery in different sites doesn't reduce the value of R&D success in either site. Even when consumers don't find much difference in products, technological distinction between the incompatible products developed from different sites, may be perceived by the producers of complementary goods which play another key role in forming incompatible systems. In that situation, if the two technologies are expected to be almost equally promising, then both technologies may capture more than the critical mass of producers of complementary goods at the same time. Then, the simultaneous discovery in different sites may lead to no "tipping" as in the case discussed by Quelin et al(2001). Recall the example in the second generation wireless telecommunication market in US where both GSM technology and CDMA technology were introduced around 1997. Even though consumers don't have specific preference for one technology over the other, both standards seem to have won the critical mass of producers of complementary goods such as handset manufacturers, so tipping will be unlikely to occur.

On the contrary, we assume that simultaneous discovery in the same site reduces the value of R&D success, which is one of the key assumption in our model.[17] How simultaneous discovery in the same site hurts each firm

[15] How the research alliance game proceeds is introduced more in detail at the beginning of Section 5.

[16] With the assumption, we exclude the case that simultaneous discovery in different sites hurts R&D success as much as simultaneous discovery in the same site does, in which firms site choice problem becomes trivial since firms' dominant strategy is choosing the same site due to compatibility externality.

[17] If simultaneous discovery in the same site results in no loss, firms site choice problem becomes trivial in that firms' dominant strategy is choosing the same site because of

depends on the situation of the relevant industries, some of which may be captured in our analysis of 3 different R&D games.

2.2.2 (Backward) compatibility externality

We assume that compatibility externality arises from choosing the same site, not depending on the result of R&D.[18] Such assumption could well fit the industries where technology evolves in a way that the next generation technology is backward compatible with the current generation technology. In that case, when a firm makes an exclusive discovery of new technology, it may easily win over the rival firm's customers since the rival firm's customers can switch to the firm with the new technology without significant switching cost. Consider again the example of wireless telecommunication industry in which firms engage in R&D for next generation of technologies. If all the firms choose the same site - GSM or CDMA, followed by exclusive R&D success by one firm, then, new services and new products from R&D success may be backward compatible with the existing systems of the rival firms. Then rival firms' customers may want to switch to the firms with new technology because they can continue to use old handsets and accessories, not having to buy new ones. Moreover, the firm with new technology may not have to incur additional interconnection cost when its new technology is compatible with the rival's old technology, which is another source of compatibility externality.[19]

Besides the compatibility externality directly occurring in the production process, there may be another compatibility benefit which arises in technology adoption process, a part of which eventually is captured by the firms who invent the technology. Suppose that both incompatible technologies are invented simultaneously, then adoption of technologies may be delayed until the intrinsic values of the two technologies turn out to be substantial enough

compatibility externality.

[18]We exclude the case that compatibility externality arises even when firms choose different sites. But, in some cases, different standards which were originally incompatible become compatible after installing "adapters" at some costs, of which case is discussed in 7.1.

[19]This production side compatibility externality was the major factor in many wireless communication service operator's choosing 2G technologies. For details, see Fernando Saurez, 3G : Technology To Competitive Advantage, London School of Business at http://www.3gea.com/doc/Fernando%20Suarez.ppt.

that the producers of complementary goods are sure that both will survive.[20] However, if both firms investigate the same site so that the technologies developed from the site are known to be compatible, then the suppliers of complementary goods would have no fear of being stranded, so there will be no delay in adoption, which is another source of compatibility externality.[21]

3 The Bertrand R&D game

In this section, we consider the Bertrand R&D game where firms compete away the reward from R&D success in the case of simultaneous discovery following firms' choosing the same site.

3.1 Firms' optimal effort choice (2nd stage)

First we examine firms' equilibrium effort choice conditional on site choice determined in the first stage. Then, there are 4 different cases for site choices : $(S_1, S_1), (S_1, S_2), (S_2, S_1), (S_2, S_2)$. But, since sites are symmetric, firms' choice problem of the optimal effort level given the site choice (S_1, S_1) is identical to that given the site choice (S_2, S_2). By the same reason, the optimal effort choice problem given (S_1, S_2) is identical to that given (S_2, S_1) for both firms. Hence it suffices to analyze only the two cases, $(S_1, S_1), (S_1, S_2)$, each of which we call as duplication and as differentiation respectively in the rest of the paper.

3.1.1 Subgame following duplication

Now suppose both firms choose S_1. Then, the firm i' payoff maximization problem, conditional on both firms being at S_l is

$$Max_{\pi_i^S}\{\pi_i^S(1-\pi_j^{S*})V(2)-c(\pi_i^S)\}$$

[20]As mentioned earlier, the failure of the AM stereo standards provides one example that the adoption delay due to lack of compatibility may be huge, implying that no delay due to compatibility may be huge.

[21]For example, in Europe where GSM was determined by ETSI for a single wireless telecommunication standard, all the European operators have adopted GSM without significant delay. In contrast, in the US where multiple standards were allowed, the 2G technologies were introduced far later than in Europe.

where $i \in \{A, B\}$ with $i \neq j$ and π_j^{S*} solves the firm j's maximization problem for given $V(2)$, conditional on duplication.[22] Then, the first order condition for the firm i's maximization problem is solved by π_i^{S*} as

$$(1 - \pi_j^{S*})V(2) = c'(\pi_i^{S*}).$$

The left-hand side of the first order condition represents the firm i's marginal revenue from increase in effort conditional on duplication, while the right-hand side of the condition represents the firm i's marginal cost of increase in effort. Note that the firm i's marginal revenue consists of the two parts, $(1-\pi_j^{S*})$ and $V(2)$, where $(1-\pi_j^{S*})$ is the probability of an exclusive discovery given the firm i's R&D success. It shows that in the Bertrand R&D game where simultaneous discovery yields no reward to any firm, a firm has less incentive to increase its effort as the rival firm's effort level is higher because the rival firm's higher effort level (hence probability of success) leads to simultaneous discovery with higher probability, which in turn results in less probability of an exclusive discovery, thereby yielding less marginal revenue from the same effort level.

But note that π_j^{S*} should be equal to π_i^{S*} in the equilibrium by symmetry between firms. Hence it follows that $(1 - \pi_j^{S*})V(2) = (1 - \pi_i^{S*})V(2)$, which is decreasing in π_i^{S*} in the equilibrium. Using this fact, we can analyze the firm i's equilibrium effort choice using Figure 1.

In Figure 1, the vertical axis intercept of the straight line representing $(1 - \pi_j^{S})V(2)$ is $V(2)$. The figure shows that the marginal revenue for given π_i is increasing in $V(2)$ so that π_i^{S*} also should be increasing in $V(2)$ with the increasing marginal cost function.

Now consider the social planner's choice problem on the efficient effort level, conditional on both being at S_1, which is

$$Max_{\pi_A^S, \pi_B^S}\{[1 - (1 - \pi_A^S)(1 - \pi_B^S)]V(2) - c(\pi_A^S) - c(\pi_B^S)\}.$$

Then, the first order conditions for the social planner's problem are solved by π_i^{S**} as

$$(1 - \pi_j^{S**})V(2) = c'(\pi_i^{S**}) \text{ for } i, j \in \{A, B\} \text{ with } i \neq j,$$

where $(\pi_A^{S**}, \pi_B^{S**})$ solves the social planner's maximization problem for given $V(2)$, conditional on duplication. The left-hand side of the condition represents the social marginal revenue from increase in effort in the firm i's R&D

[22] Since when a firm chooses its optimal effort level, it considers its rival's effort level, $\pi_j^{S*}$is the best response to π_i^{S*}, the rival's equilibrium effort level for given $V(2)$.

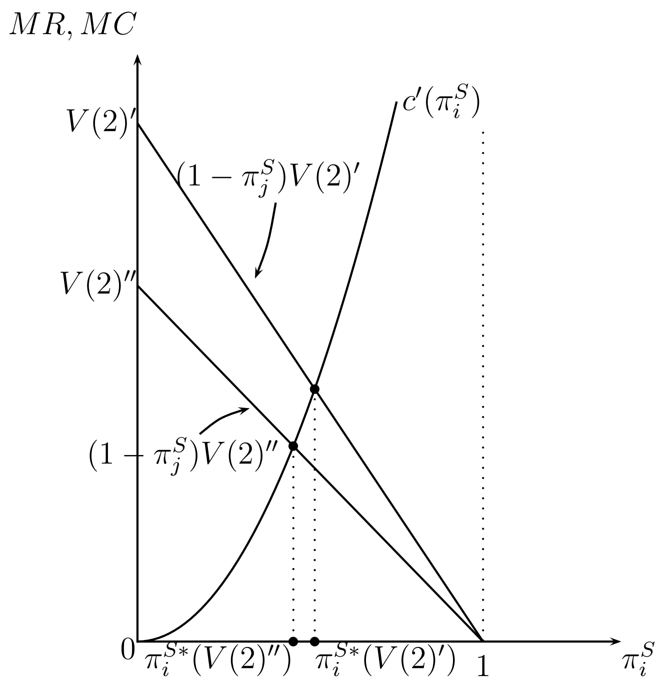

Figure 1: π_i^{S*} increases in $V(2)$

activity conditional on duplication, while the right-hand side of the condition represents the social marginal cost of increase in effort in the firm i's R&D activity. Note that $(1-\pi_j^{S**})V(2)$, the social marginal revenue from increasing π_i^{S**} decreases in π_j^{S**} ; as the other firm j is more likely to succeed in R&D, the social value of the firm i's effort is less since the firm i's success in R&D yields no social value given the firm j's success in R&D.

Now compare the equilibrium effort level with the socially optimal effort level using the corresponding first order conditions. Note that the strict convexity of $c(\cdot)$ ensures the uniqueness of π_i^{S*} and π_i^{S**} for given $V(2)$ in each of the first order conditions. Then, it follows that $\pi_i^{S*} = \pi_i^{S**}$ for $i \in \{A, B\}$ since π_i^{S*} and π_i^{S**} are the unique solutions of the identical equations. Therefore, the firms' equilibrium effort levels are efficient when firms duplicate site choice.

3.1.2 Subgame following differentiation

Now denote by π_i^D the firm i's effort level (hence the probability) when firms choose different sites. Suppose that the firm A chooses S_1 and the firm B chooses S_2. Then, the firm A's payoff maximization problem conditional on the firm B being at S_2 is

$$Max_{\pi_A^D}\{\pi_A^D V(1) - c(\pi_A^D)\}.$$

Then, π_A^{D*}, the firm A's equilibrium effort level conditional on differentiation solves the first order condition of the firm A's problem as

$$V(1) = 1 = c'(\pi_A^{D*}).$$

The left-hand side of the condition represents the firm A's marginal revenue from increase in effort conditional on the firm B's being at the different site, while the right-hand side of the condition represents the firm A's marginal cost of increase in effort. Since firms are symmetric, π_B^{D*}, the firm B's equilibrium effort level solves the first order condition for the firm B's payoff maximization problem as

$$V(1) = 1 = c'(\pi_B^{D*}).$$

Note that being different from the duplication case, the probability of an exclusive discovery is 1. Given assumption on $V(1)$, the marginal revenue from increase in effort is constant so that $V(1)$ and the marginal cost combine to determine π_i^{D*} as in Figure 2.

Now consider the social planner's optimal effort choice problem conditional on the firms' being at different sites, which is

$$Max_{\pi_A^D,\pi_B^D}\{\pi_A^D V(1) + \pi_B^D V(1) - c(\pi_A^D) - c(\pi_B^D)\}.$$

Then, π_i^{D**} for $i \in \{A, B\}$ for given $V(1)$, solves the first order conditions for the social planner's problem as

$$V(1) = 1 = c'(\pi_i^{D**}) \text{ for } i, j \in \{A, B\} \text{ with } i \neq j.$$

Then, by the same argument used to demonstrate the efficiency of the equilibrium effort conditional on duplication, we have $\pi_i^{D*} = \pi_i^{D**}$ for $i \in \{A, B\}$, so the firms' equilibrium effort levels are efficient when firms differentiate site choice.

The efficiency result in the equilibrium effort in the subgames is summarized as in the following proposition.

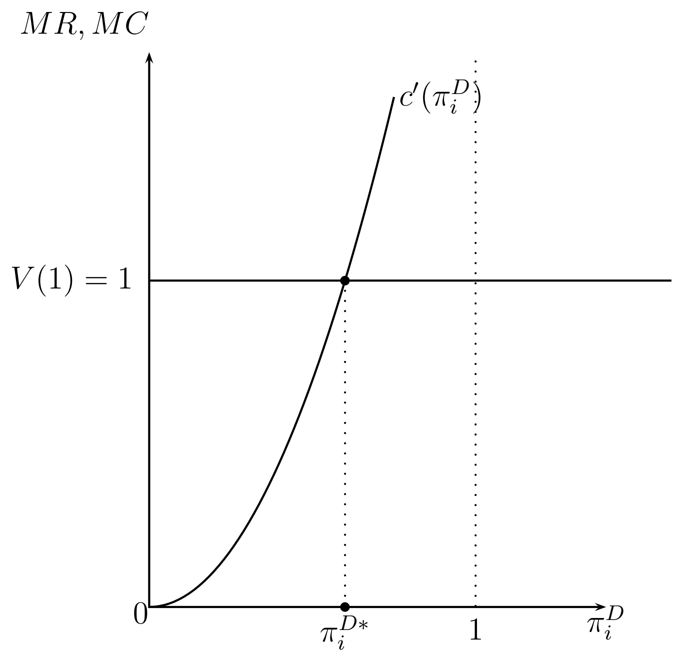

Figure 2: π_i^{D*} is uniquely determined by $c(\cdot)$ and $V(1) = 1$.

Proposition 1 ***(Efficient Effort)*** *In the subgame of the Bertrand R&D game, where firms choose the optimal effort level given site choice, the equilibrium effort levels are efficient conditional on the site choice both when firms duplicate site choice and when firms differentiate site choice.*

The efficiency result in the equilibrium effort choice in the duplication subgame is caused by the unique incentive structure inherent in the Bertrand R&D game and is in contrast to the typical result of over-investment in R&D which is found in Loury (1979), Reinganum (1979, 1982) and Dasgupta and Stiglitz (1980).

3.1.3 Comparison between the two subgames

Now compare the equilibrium effort level conditional on firms' being at different sites to that conditional on firm's being at the same site. Then, we

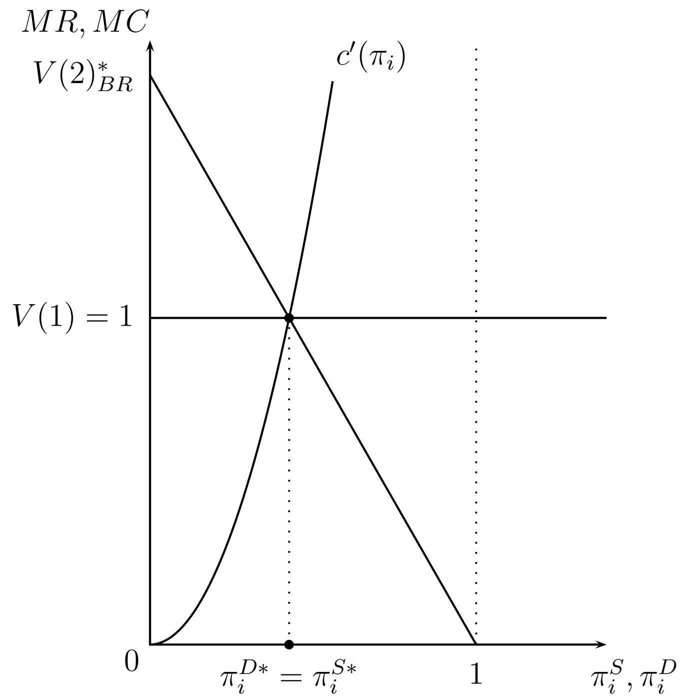

Figure 3: $\pi_i^{D*} = \pi_i^{S*}$ as $V(2) = V(2)^*_B$

need to compare the corresponding first order conditions,

$$(1 - \pi_j^{S*})V(2) = c'(\pi_i^{S*}) \text{ and } V(1) = 1 = c'(\pi_i^{D*}).$$

Since $c'(\cdot)$ is strictly convex, it suffices to compare the left-hand side of each equation. Now, refer to $V(2)$ as $V(2)^*_{BR}$ if $V(2) = \frac{1}{(1-\pi_i^{D*})}$. Then, Figure 3 shows that $V(2)^*_{BR}$ is unique with increasing $c'(\pi_i)$.

Note that π_i^{S*} depends on the magnitude of $V(2)$, while π_i^{D*} is fixed for given $c'(\cdot)$ and for given $V(1) = 1$. Then, the following claim provides the condition under which we can compare π_i^{S*} to π_i^{D*}.

Claim 1 *In the subgame of the Bertrand R&D game, where firms choose the optimal effort level given site choice, the equilibrium effort level conditional on duplication is greater than that conditional on differentiation if and only if* $V(2) > V(2)^*_{BR}$ *where* $V(2)^*_{BR} = \frac{1}{(1-\pi_i^{D*})}$.

Proof. See Appendix. ■

Given fixed π_i^{D*}, the result in Claim 1 implies that π_i^{S*} increases in $V(2)$. It is very intuitive in that with higher compatibility externality, the marginal effort revenue conditional on duplication rises accordingly so that it may more than offset the expected loss from the possibility of simultaneous discovery, yielding higher equilibrium effort level.

The result of Claim 1 differs from the result of Chatterjee and Evans (2003) and Loury (1979), in which research intensity falls as the number of rival firms increases. But, their results without compatibility externality can be captured as a special case of our model by putting $V(2) = 1$. Since $V(2) = 1 < \frac{1}{(1-\pi_i^{D*})}$, it follows that $\pi_i^{S*} < \pi_i^{D*}$ according to Claim 1, as same as in Chatterjee and Evans(2003) and in Loury (1979). But our model shows that such results in Chatterjee and Evans(2003) and in Loury (1979) may not be true with big enough compatibility externality, in which R&D intensity may rise with the number of firms if compatibility externality increases in the number of firms.

3.2 Firms' optimal site choice (1st stage)

Denote by $W_i(S_k, S_l)$ the firm i's expected payoff from choosing the site S_k where all the firms choose the optimal effort level conditional on the site choice (S_k, S_l) where $i \in \{A, B\}$ and $S_k, S_l \in \{S_1, S_2\}$. Denote by $W(S_k, S_l)$ the social value of the site choice, (S_k, S_l) where the effort level in each site is efficient conditional on the site choice (S_k, S_l). Since $\pi_i^{S*} = \pi_j^{S*}$ in the equilibrium due to symmetry between firms, we let π_{BR}^{S*} the equilibrium effort level in the Bertrand R&D game when both firms choose the same site where $\pi_i^{S*} = \pi_j^{S*} = \pi_{BR}^{S*}$. Denote by π^{S**} the socially optimal effort level when firms choose the same site.[23] Similarly, denote by π^{D*} and π^{D**} the equilibrium effort level and the socially optimal effort level respectively when firms choose different sites.

Then, consider first $W(S_1, S_1)$ and $W(S_1, S_2)$ where

[23]Since the social planner's problem is identical across different games, the socially optimal effort level conditional on site choice is identical across different games, too. So we have one notation for the socially optimal effort level. Similarly, the payoff conditional on differentiation is identical across different games, so we have one notation for the equilibrium effort level conditional on differentiation.

$$\begin{aligned} W(S_1,S_1) &= \pi_1^{S**}(2-\pi_1^{S**})V(2) - 2c(\pi_1^{S**}) \text{ and} \\ W(S_1,S_2) &= \pi_1^{D**} + \pi_2^{D**} - c(\pi_1^{D**}) - c(\pi_2^{D**}). \end{aligned}$$

Also consider $W_B(S_1, S_1)$ and $W_B(S_1, S_2)$ where

$$\begin{aligned} W_B(S_1,S_1) &= \pi_1^{S*}(1-\pi_1^{S*})V(2) - c(\pi_1^{S*}) \text{ and} \\ W_B(S_1,S_2) &= \pi_2^{D*} - c(\pi_2^{D*}). \end{aligned}$$

Note that $W(S_l, S_l)$ with $S_l \in \{S_1, S_2\}$ depends on the magnitude of $V(2)$, while $W(S_l, S_k)$ with $l \neq k$ is independent of $V(2)$. Especially, $W(S_l, S_l)$ is strictly increasing in $V(2)$. Similarly, $W_i(S_l, S_l)$ with $i \in \{A, B\}$ is strictly increasing in $V(2)$, while $W_i(S_l, S_k)$ with $i \in \{A, B\}$ is independent of $V(2)$. Then, the result on the equilibrium of the Bertrand R&D game is summarized in Proposition 2.

Proposition 2 *In the subgame perfect Nash equilibrium of the Bertrand R&D game, (i) if compatibility externality is small enough that* $V(2) < V(2)^*_{BR}$*, then firms choose different sites in the first stage and exert* π^{D*} *in the second stage, (ii) if compatibility externality is big enough that* $V(2) > V(2)^*_{BR}$*, then firms choose the same site in the first stage and exert* π^{S*}_{BR} *in the second stage.*

Proof. See Appendix. ■

Proposition 2 shows that if compatibility externality is big enough, then firms prefer duplication regardless of possibility of simultaneous discovery in the equilibrium.

Now denote by $V(2)^{**}$ the reward from R&D success conditional on both firms being on the same site for which $W(S_l, S_l) = W(S_l, S_k)$ for $S_l \in \{S_1, S_2\}$ with $l \neq k$. Then, the social optimum depends on $V(2)$ as summarized in the following proposition.

Proposition 3 *In the stoical optimum of the Bertrand R&D game, (i) if compatibility externality is small enough that* $V(2) < V(2)^{**}$*, then firms choose different sites in the first stage and exert* π^{D**} *in the second stage, (ii) if compatibility externality is big enough that* $V(2) > V(2)^{**}$*, then firms choose the same site in the first stage and exert* π^{S**} *in the second stage.*

Proof. See Appendix. ■

Proposition 2 and Proposition 3 shows that both in the equilibrium and in the social optimum, site choice is monotone in $V(2)$ in the sense that as compatibility externality becomes greater, duplication is not only more socially desirable but also more preferred by firms. Now, we have the following result on the relation between $V(2)^*_{BR}$ and $V(2)^{**}$.

Lemma 1 *For given $c(\cdot)$, $V(2)^*_{BR}$ is strictly greater than $V(2)^{**}$.*

Proof. See Appendix. ■

Due to such discrepancy between $V(2)^{**}$ and $V(2)^*_{BR}$ as in Lemma 1, the equilibrium site choice exhibits too much differentiation as summarized in Proposition 4.

Proposition 4 *(**Excess Differentiation**) Suppose that compatibility externality is such that $V(2)^{**} < V(2) < V(2)^*_{BR}$. Then, in the Bertrand R&D game, the equilibrium is inefficient due to excess differentiation in site choice even though the equilibrium effort level given duplication is efficient.*

Proof. See the Appendix. ■

The excess differentiation is caused by the following discrepancy between the private incentive and the social incentive in site choice : When a firm decides to choose another site, it doesn't consider the other firm's loss in expected payoff from foregone compatibility externality. But if $V(2) > V(2)^*_{BR}$, then compatibility externality is big enough to more than offset the gap between the private incentive for duplication and that of the social planner, so firms choose the same site even from noncooperative motive.

4 The equal sharing R&D game

In this section, we consider the equal sharing R&D game where firms share a half of the reward from R&D success in the case of simultaneous discovery. The equal sharing R&D game may capture the industries in which instant imitations follows initial innovations. For example, consider the industries where the relevant intellectual property right(IPR hereafter)s are not well defined and competing firms have enough ability for instant R&D. In such industries, one firm's success in R&D may induce competing firms to instantly engage in R&D whenever firms know that instant imitations will not lead to dissipation of all the firms' profits.[24]

4.1 Firms' optimal effort choice (2nd stage)

4.1.1 Subgame following duplication

Suppose both firms choose S_1. Then, the firm i's maximization problem, conditional on both firms being at S_1 is

$$Max_{\pi_i^S}\{[\frac{1}{2}(\pi_i^S)(\pi_j^{S*})+\pi_i^S(1-\pi_j^{S*})]V(2)-c(\pi_i^S)\} \text{ for } i,j\in\{A,B\} \text{ with } i\neq j$$

where π_j^{S*} solves the firm j's maximization problem for given $V(2)$. Then, the first order condition for the firm i's problem conditional on both being at S_1 is

$$[\frac{1}{2}(\pi_j^{S*})+(1-\pi_j^{S*})]V(2)=[1-\frac{1}{2}\pi_j^{S*}]V(2)=c'(\pi_i^{S*}) \text{ for } i,j\in\{A,B\} \text{ with } i\neq j.$$

Now, recall that the difference in the payoff structure between the Bertrand R&D game and the equal sharing R&D game lies only in the difference in the firms' payoffs in the occasion of simultaneous discovery. Hence, the social planner's effort choice problem conditional on both being at S_1 is same as in the Bertrand R&D game, which is

$$Max_{\pi_A^S,\pi_B^S}\{[1-(1-\pi_A^S)(1-\pi_B^S)]V(2)-c(\pi_A^S)-c(\pi_B^S)\},$$

as in the Bertrand R&D game. Accordingly the first order conditions with respect to π_i^S, are also same as in the Bertrand R&D game and

$$(1-\pi_j^{S**})V(2)=c'(\pi_i^S) \text{ for } i,j\in\{A,B\} \text{ with } i\neq j.$$

Note that $[1-\frac{1}{2}\pi_j^{S*}]V(2)$, the firm i's the marginal effort revenue is always greater than $(1-\pi_j^{S**})V(2)$ for each π_i and given $V(2)$ in the equilibrium. Hence, it follows that $\pi_i^{S**}<\pi_i^{S*}$ for given $V(2)$ as shown in Figure 4.

[24]For the R&D race in which one firm's innovation induces another firms' participation in R&D race in a different setting, see Choi(1991).

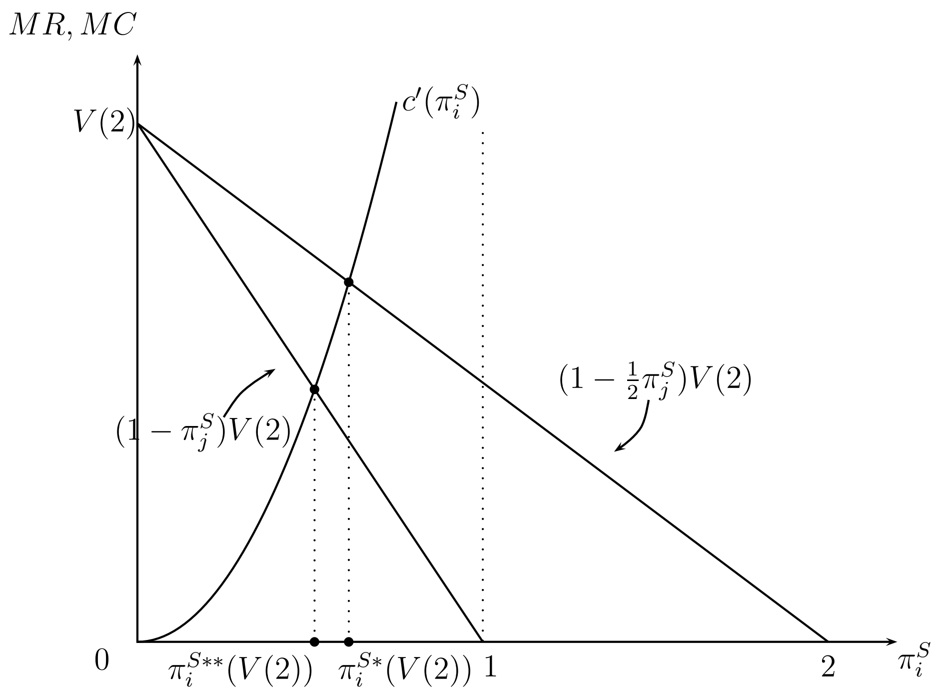

Figure 4: $\pi_i^{S**} < \pi_i^{S*}$ for given $V(2)$

4.1.2 Effort choice following differentiation

The equilibrium effort level conditional on firms' choosing different sites is same as in the Bertrand R&D game. So the relevant first order condition is

$$V(1) = 1 = c'(\pi_i^{D*}) \text{ for } i, j \in \{A, B\} \text{ with } i \neq j.$$

Hence as in the Bertrand R&D game, it follows that $\pi_i^{D*} = \pi_i^{D**}$ for $i \in \{A, B\}$.

The results on the equilibrium effort level in the subgames of the equal sharing R&D game is summarized in the following proposition.

Proposition 5 ***(Excessive Effort)*** *In the equal sharing R&D game, the equilibrium effort level is inefficiently high in the subgame where firms choose the same site, while the equilibrium effort level is efficient in the subgame where firms choose different sites.*

The inefficiency in the equilibrium effort level conditional on duplication is in contrast to the efficiency result in the Bertrand R&D game. Such inefficiency result is caused by the over-rewarding structure in the equal sharing R&D game as follows. Note that the social marginal revenue from increase in the firm i's effort is $(1-\pi_j)V(2)$, implying the firm i's marginal contribution to R&D success is worth only to the extent that it backs up the other firm's investigation. But, in the equal sharing R&D game, each firm gets $(1-\frac{1}{2}\pi_j)V(2) = \frac{1}{2}V(2) + (1-\pi_j)V(2)$ for its marginal effort revenue, which implies that each firm is over-rewarded by $\frac{1}{2}V(2)$, creating excessive incentive for duplication.

4.1.3 Comparison between the two subgames

Now we examine the difference between the equilibrium effort level conditional on firms' choosing the same site and that conditional on firms' choosing different sites. As in the previous section on the Bertrand R&D game, we need to compare the left-hand sides of the first order conditions : $[1-\frac{1}{2}\pi_j^{S*}]V(2)$ and $V(1) = 1$. Now refer to $V(2)$ as $V(2)^*_{ES}$ if $V(2) = \frac{1}{1-\frac{1}{2}\pi^{D*}}V(2)$. Also denote by π^{S*}_{ES} the equilibrium effort level in the equal sharing R&D game. Then, the following claim provides the condition under which we can compare π^{D*} to π^{S*}_{ES}.

Claim 2 *In the subgame of the equal sharing R&D game, π^{D*}, the equilibrium effort level conditional on differentiation is greater than π^*_{ES}, the equilibrium effort level conditional on duplication if and only if $V(2) < V(2)^*_{ES}$ where $V(2)^*_{ES} = \frac{1}{1-\frac{1}{2}\pi^{D*}}V(2)$.*

Proof. See Appendix. ■

4.1.4 Firms' optimal site choice (1st stage)

As in the Bertrand R&D game, the social planner's expected payoffs from duplication and from differentiation are respectively

$$\begin{aligned} W(S_l, S_l) &= \pi_l^{S**}(2-\pi_l^{S**})V(2) - 2c(\pi_l^{S**}) \text{ and} \\ W(S_l, S_k) &= \pi_l^{D**} + \pi_k^{D**} - c(\pi_l^{D**}) - c(\pi_k^{D**}). \end{aligned}$$

The firm i's expected payoff from differentiation and duplication are respectively

$$\begin{aligned} W_i(S_l, S_l) &= \frac{1}{2}\pi_l^{S*}(2-\pi_l^{S*})V(2) - c(\pi_l^{S*}) \text{ and} \\ W_i(S_l, S_k) &= \pi_l^{D*} - c(\pi_l^{D*}). \end{aligned}$$

when the firm i chooses the site S_l. The results on the equilibrium in the equal sharing R&D game is summarized in Proposition 6.

Proposition 6 *In the subgame perfect Nash equilibrium of the equal sharing R&D game, (i) if compatibility externality is small enough that $V(2) < V(2)^*_{ES}$, then firms choose different sites in the first stage and exert π^{D*} in the second stage, (ii) if compatibility externality is big enough that $V(2) > V(2)^*_{ES}$, then firms choose the same site in the first stage and exert π^{S*}_{ES} in the second stage.*

Proof. See Appendix. ■

Proposition 6 shows that in the equal sharing R&D game, site choice is monotone in $V(2)$ in the sense that duplication is more preferred and more desirable as compatibility externality becomes greater as in the Bertrand R&D game.

Now, we have the following result on the relation between $V(2)^{**}$ and $V(2)^*_{ES}$.

Lemma 2 *For given $c(\cdot)$, $V(2)^*_{ES}$ is strictly smaller than $V(2)^{**}$.*

Proof. See Appendix. ■

Then, with Lemma 2, we have the following excess duplication result on the equilibrium of the equal sharing R&D game.

Proposition 7 ***(Double Inefficiency)*** *Suppose that compatibility externality is such that $V(2) > V(2)^*_{ES}$. In the equal sharing R&D game, the equilibrium is inefficient as follows. (1) For $V(2)$ with $V(2)^{**} < V(2)$, the* *equilibrium site choice is efficient but the equilibrium effort level given duplication is higher than in the social optimum. (2) For $V(2)$ with $V(2)^{*}_{ES} < V(2) < V(2)^{**}$, the equilibrium exhibits both excess duplication in site choice and excess effort level given duplication.*

Proof. See Appendix. ■

From Proposition 7, one can see that even when compatibility externality is big enough that firms' site choice of duplication is efficient, the inefficiency involved in excessive effort still remains in the equilibrium. This comes from the over-rewarding payoff structure for simultaneous discovery in the equal sharing R&D game as shown in Proposition 5. However, if compatibility externality has a intermediate value such that firms find it optimal to duplicate, but it is still not big enough for duplication for the social planner, then excess duplication in site choice worsens the inefficiency problem.

5 The Research Alliance game

Now in this section we consider a semi-cooperative game in which firms cooperate in site choice by forming a research alliance and then compete in R&D by investigating the site independently.[25] Consider the following situation. The firm A and the firm B choose a site to investigate sequentially where the firm A chooses first by which it obtains exclusive legal rights on fundamental technologies relevant to the site.[26] In such situation, the firm B can choose the same site chosen by the firm A only when the firm A allows the firm B to do so. However, due to symmetry between firms, the firm A also finds it better off to exploit compatibility externality whenever the firm B does so. Hence, whenever there exists compatibility externality big enough that the firm B wants to choose the same site chosen by the firm A, the firm

[25] We label as a semi-cooperative game the research alliance game we consider in this section in the sense that firms cooperate in forming a research alliance from a non-cooperative motive. Especially, in the research alliance game, how firms form a research alliance and how the firms choose a joint action, are explicitly specified. So, the research alliance game we consider in this subsection is not a cooperative game but just another noncooperative game in which forming a coalition is one of firms' strategies.

[26] Not only final products but also fundamental technologies are often proprietary. For example, in the pharmaceutical industries many laboratories have patents on "compounds" where compounds(fundamental technologies) are the substances which could be potentially used for the development of new drugs(final products).

A also has an incentive to allow the firm B to choose the same site as long as its first mover's advantage is properly rewarded.

Then, one of the possible ways of both firms' agreeing on choosing the same site would be forming a research alliance with a contract by which the firm B is allowed to choose the same site already chosen by the firm A and the firm A is compensated some payoffs for giving up its exclusive legal rights on the site. Especially we consider the research alliance with the following payoff structure. Suppose the firm i with $i \in \{A, B\}$ makes an exclusive discovery and the reward of $V(2)$ is realized from R&D success.[27] Then, the reward to the firm i given its exclusive discovery consists of the following two parts. The first part of its reward one is $V(1)$, referred to as the **stand-alone value of R&D success**, which is given to whoever firm makes an exclusive discovery. The second part is the firm i's share of the increase in the value of R&D success created by firms choosing the same site, referred to as the **network value of R&D success**. Reflecting the compensation for giving up its property rights on the site, the firm A receives $\frac{1+\lambda}{2}[V(2) - V(1)]$ for its share of network value of R&D success, while the firm B receives $\frac{1-\lambda}{2}[V(2) - V(1)]$ for its share of network value of R&D success where λ is the sharing parameter in $[0, 1]$.[28] More specifically, if firms agree on $\lambda > 0$, then it implies that the firms agree on the firm A being compensated for giving up its property rights on the site. If firms agree on $\lambda < 1$, then it implies that the firms agree on the firm B being compensated for its contribution to creation of compatibility externality by its choosing the same site. Suppose that the firm A is the sole discoverer, then it receives $V(1)$, the stand-alone value of R&D success for the reward for its exclusive discovery and $\frac{1+\lambda}{2}[V(2)-V(1)]$ for the compensation for its share of network value of R&D success, while the firm B receives only its share of network value of R&D success,$\frac{1-\lambda}{2}[V(2) - V(1)]$. If the sole discoverer is the firm B, then it receives $V(1)$, the stand-alone value of R&D success for the reward for its exclusive discovery and $\frac{1-\lambda}{2}[V(2)-V(1)]$ for its share of network value of R&D success, while the firm A receives only $\frac{1+\lambda}{2}[V(2) - V(1)]$, its share of the network value of R&D success. If both firms succeed in R&D, then

[27]Recall that backward compatibility enables the firm with exclusive discovery to exploit the compatibility externality so that the firm i receives $V(2)$ instead of $V(2)$ from its exclusive discovery.

[28]The upper bounds and lower bounds of $\lambda^* \in [0, 1]$, the equilibrium sharing proportion for given $V(2)$ are analyzed in this paper, but the firms' detailed bargaining process determining λ^* is not considered in this paper.

both firms split the stand-alone value of R&D success, so each firm receive $\frac{1}{2}V(1)$ for its reward for simultaneous discovery as well as its share of the network value of R&D success. If both firms fail, then both firms get no reward. So, in the research alliance game, firms play a equal sharing R&D game for the stand-alone value of R&D success and share the network value of R&D success according to the sharing parameter λ which is determined at the time when firms agree on forming the research alliance.

Using the research alliance model with the two parts of the reward from R&D success, we can also analyze the case where firms are allowed to choose the same site noncooperatively without any explicit contract and compatibility externality is captured by all the firms choosing the same site no matter which firm discovers, given R&D success in the site. Consider the case that there exists indirect(or virtual) network effects such that firms' choosing a same standard result in a larger set of complementary goods, which in turn cause a positive feedback on the firms' own goods. Then, such benefits from a larger set of complementary goods will occur to all the firms whose products are compatible. For example, suppose one firm succeeds in the development of a hardware of the next generation based on a specific standard, which induces more developments of softwares compatible with the standard. Then, assuming that there doesn't occur much cost for the software companies to make their products to be backward compatible, the firms other than the discoverer also would receive the benefit of more variety of softwares compatible with their current generation of hardware.[29] In this case, $\lambda \neq 0$ implies that firms' benefit from compatibility externality is not same even when firms don't make the binding contract which results in asymmetric payoff. One of the examples of such case is that the firms choosing the same site has different position in the market and the benefit of compatibility externality is in proportion to each firm's market share. Then $\lambda > 0$ represents the firm A's being in the market leader in the industry.

The payoff structure in our research alliance model captures the following features which are found in many industries.[30] First, even when firms form

[29]If there are essential common parts which are used both in the current generation of products and the next generation of products, the success of the next generation of products may result in the reduction of the parts used commonly, which can be another example that non-discoverers may receive the benefit of compatibility externality given R&D success by another firm.

[30]The research alliance that we consider is different from other typical type of research joint ventures, the major function of which is in the reduction of R&D cost. For the

a research alliance, they still compete against each other. In our research alliance model, firms cooperate by forming a research alliance in creating compatibility externality to increase the value of R&D success, but they still compete for the stand-alone value of R&D success by investigating the site independently. Second, compatibility externality can be captured by every firm choosing the same standard even when the success in R&D is made by another firm.[31] This case can be captured by allowing λ to be strictly smaller than 1 in our model. Third, the first mover's advantage is acknowledged in sharing the value of R&D success. This case can be captured by allowing λ to be strictly greater than 0 in our model.

Now consider each firm's expected revenue when the firms form a research alliance to investigate S_1.

$$\begin{aligned}
V_A(S_1, S_1) &= [\pi_A(1-\pi_B) + \frac{1}{2}\pi_A\pi_B]V(1) + \\
&\quad \frac{1+\lambda}{2}[\pi_A(1-\pi_B) + \pi_B(1-\pi_A) + \pi_A\pi_B][V(2) - V(1)] \\
&= \frac{1}{2}\pi_A(2-\pi_B) + \frac{1+\lambda}{2}(\pi_A + \pi_B - \pi_A\pi_B)[V(2) - 1], \text{ and} \\
V_B(S_1, S_1) &= [\pi_B(1-\pi_A) + \frac{1}{2}\pi_B\pi_A]V(1) + \\
&\quad \frac{1-\lambda}{2}[\pi_A(1-\pi_B) + \pi_B(1-\pi_A) + \pi_A\pi_B][V(2) - V(1)] \\
&= \frac{1}{2}\pi_B(2-\pi_A) + \frac{1-\lambda}{2}(\pi_A + \pi_B - \pi_A\pi_B)[V(2) - 1],
\end{aligned}$$

where $\lambda \in [0, 1]$.

The first term in each firm's expected revenue represents the expected reward of a stand-alone value of R&D success. The second term in each firms's expected revenue represents the expected reward of its share in a network value of R&D success which reflects the first mover's advantage. For example, with $\lambda = 1$, the firm A enjoys the first mover's advantage in full and gets all the network value of R&D success, while with $\lambda = 0$, there's no first mover's advantage and each firm shares the network value equally.

analysis of such type of research joint ventures, see Bloch (1995), Yi (1998), and Yi.& Shin (2000).

[31] As discussed, this can be applicable to the case that firms don't make a explicit contract.

5.1 Firms' optimal effort choice (2nd stage)

Now we consider the firms' effort choice in each subgame. Suppose that in the first stage firms have formed a research alliance to investigate S_l with $S_l \in \{S_1, S_2\}$ in which they split the network value of R&D success according to the sharing parameter λ. Then, the firm A's maximization problem, conditional on being the first mover in the research alliance is

$$Max_{\pi_A^S}\{\pi_A^S(1-\pi_B^{S*})+\frac{1}{2}\pi_A^S\pi_B^{S*}]+\frac{1+\lambda}{2}[(\pi_B^{S*}+(1-\pi_B^{S*})\pi_A^S)][V(2)-1]-c(\pi_A^S)\}$$

where π_B^{S*} solves the firm B's maximization problem for given $V(2)$ and λ. Then, π_A^{S*}, the firm A's optimal effort level should solve the following first order condition,

$$(1-\frac{1}{2}\pi_B^{S*})+\frac{1+\lambda}{2}(1-\pi_B^{S*})[V(2)-1]=c'(\pi_A^S).$$

Now consider the firm B's maximization problem.

$$Max_{\pi_B^S}\{[\pi_B^S(1-\pi_A^{S*})+\frac{1}{2}\pi_B^S\pi_A^{S*}]+\frac{1-\lambda}{2}[\pi_A^{S*}+\pi_B^S(1-\pi_A^{S*})][V(2)-1]-c(\pi_B^S)\}.$$ [32]

Then, π_B^{S*}, the firm B's optimal effort level should solve the following first order condition,

$$(1-\frac{1}{2}\pi_A^{S*})+\frac{1-\lambda}{2}(1-\pi_A^{S*})[V(2)-1]=c'(\pi_B^S).$$

Now, recall that the social planner's effort choice problem conditional on both being at S_l is

$$Max_{\pi_A^S,\ \pi_B^S}\{[1-(1-\pi_A^S)(1-\pi_B^S)]V(2)-c(\pi_A^S)-c(\pi_B^S)\},$$

and its corresponding first order condition is

$$(1-\pi_j^{S**})V(2)=c'(\pi_i^S) \text{ for } i,j\in\{A,B\} \text{ with } i\neq j.$$

By comparing the left hand side of the two first order conditions as in the other two noncooperative games, one can compare the equilibrium effort level

[32] If we allow firms to choose the effort level sequentially, i.e., the firm A chooses its optimal effort level first and the firm B choose its own optimal effort level later, then the subgame reduces down to the Stackelberg game where π_B^{S*} is the function of π_A^{S*}.

to the socially optimal effort level conditional on duplication. Now, recall that the subgame following differentiation in the research alliance game is identical to the corresponding subgames in the Bertrand R&D game and the equal sharing R&D game. So, if firms choose different sites in the first stage, then firms' equilibrium effort choice following differentiation in site choice is efficient as proven in Proposition 2. The equilibrium effort choice following duplication in site choice is summarized as in the following proposition.

Proposition 8 ***(Asymmetric and Non-monotonic Effort Choice)*** *Suppose that the firms have formed the research alliance in the first stage in the research alliance game. Then, the firms' equilibrium effort choices in the second stage are as follows.*
(1) If $V(2) > V(2)^*_{BR}$*, then* $\pi^{S*}_B < \pi^{S**}$ *for* $\forall\ \lambda \in [0,1]$*, while* π^{S*}_A *may be higher or lower than* π^{S**}*, depending on* λ *for given* $V(2)$*.*
(2) If $V(2)^*_{RA} < V(2) < V(2)^*_{BR}$*, then* $\pi^{S*}_A > \pi^{S**}$ *for* $\forall\ \lambda \in [0,1]$*, while* π^{S*}_B *may be higher or lower than* π^{S**}*, depending on* λ *for given* $V(2)$*.*

Proof. See the Appendix. ■

The asymmetric inefficiency in the equilibrium effort choice follows from the asymmetry in the payoff structure caused by the first mover's advantage. Since firms are symmetric in the cost structure, the asymmetric investment resulting from the asymmetric payoff structure causes inefficiency. However, note that the equilibrium effort level is inefficient in an non-monotonic way in the sense that excessive effort are more probable to be made in the equilibrium for $V(2)$ with $V(2) > V(2)^*_{BR}$, while insufficient efforts are more probable to be made in the equilibrium for $V(2)$ with $V(2) > V(2)^*_{BR}$. This non-monotonic pattern of inefficiency is caused by the interplay of the over-rewarding for simultaneous discovery and the free-riding on spill-over in the payoff structure in the research alliance. Recall that the expected reward of a network value of R&D success is shared among the firms. Hence, even though the reward of a stand-alone value of R&D success is allocated to the discoverer, a part of the expected reward of a network value of R&D success may be allocated to a non-discoverer since it is shared according to the pre-determined λ regardless of who discovers. Such reward system creates an incentive to free-ride on the rival's effort, which could potentially results in insufficient equilibrium effort as occurring when $V(2) > V(2)^*_{BR}$. However, note that there exists another force working in the opposite way, which is related to the equal sharing payoff structure for the stand-alone value of R&D success. Since firms play a equal sharing R&D game for a stand-alone value of R&D success, there's potential incentive for excessive effort as seen in the previous section. Those conflicting forces offset each other when $V(2) = V(2)^{S*}_{BR}$. And when $V(2) < V(2)^{S*}_{BR}$, the incentive for excessive effort dominates, while the incentive for insufficient effort dominates when $V(2) > V(2)^{S*}_{BR}$.

When it comes to the case without the first mover's advantage, the asymmetric inefficiency between the firms' equilibrium effort level disappears and only the non-monotonic inefficiency remains. Denote by $W_i(S_l, S_l; V(2), \lambda = 0)$ the firm i's expected payoff when both firms have chosen the same site S_l in the first stage and exert the equilibrium effort, π_i^{S*} for given $V(2)$ and $\lambda = 0$ in the second stage. Then, the case without the first mover's advantage provides the necessary and sufficient condition for duplication in site choice as shown in the following lemma.

Lemma 3 *For given $V(2)$, firms choose the same site in the equilibrium if and only if $W_B(S_l, S_l; V(2), \lambda = 0) \geq W_B(S_l, S_k)$.*[33]

Proof. See the Appendix. ■

The necessary and sufficient condition for duplication in Lemma 3 follows from the fact that the firm A can find some $\lambda \in [0, 1]$ such that both firms find it better off to form a research alliance whenever $W_B(S_l, S_l; V(2), \lambda = 0) \geq W_B(S_l, S_k)$. Then, the inefficiency in the firm's equilibrium effort choice in the case with $\lambda = 0$ can be summarized as follows.

Claim 3 ***(Non-monotonic Effort Choice without First mover's advantage)*** *Suppose there doesn't exist the first mover's advantage, i.e. $\lambda = 0$, then firms equilibrium effort choice in the research alliance exhibits the non-monotonic inefficiency as follows.*
(1) $\pi_i^{S*} > \pi_i^{S**}$ for all $V(2) \in [V(2)^*_{RA}, V(2)^*_{BR})$ and $i \in \{A, B\}$;
(2) $\pi_i^{S*} < \pi_i^{S**}$ for all $V(2)$ with $V(2) > V(2)^*_{BR}$ and $i \in \{A, B\}$.

Proof. See the Appendix. ■

Since the firms' effort incur R&D activity cost which can be considered as investment, we have the following insufficient investment result from Proposition 8 and Claim 3.

[33] We assume that firms choose the same site if $W_B(S_l, S_l; V(2), \lambda = 0) = W_B(S_l, S_k)$.

Corollary 1 ***(Under-Investment with big compatibility externality)*** *Suppose that compatibility externality is big enough that $V(2) > V(2)^*_{BR}$. If the first mover's advantage is not big enough so that the two firms share the network value of R&D success almost equally, the firms' equilibrium investment choice exhibits under-investment.*

As discussed earlier, when compatibility externality is big enough, then the incentive for free-riding on the rival firm's effort outweighing the incentive for excessive effort inherent in the equal-sharing payoff structure, which results in the under-investment result as in Corollary 1.

5.2 Firms' optimal site choice (1st stage)

As in the previous two noncooperative R&D games, the social planner's expected payoffs from duplication and the expected payoffs from differentiation are respectively

$$\begin{aligned} W(S_l, S_l) &= \pi_l^{S**}(2 - \pi_l^{S**})V(2) - 2c(\pi_l^{S**}) \text{ and} \\ W(S_l, S_k) &= \pi_l^{D**} + \pi_k^{D**} - c(\pi_l^{D**}) - c(\pi_k^{D**}). \end{aligned}$$

The firm i's expected payoff in the research alliance and the payoff conditional on differentiation are respectively

$$\begin{aligned} W_A(S_l, S_l) &= \pi_A^{S*}(1 - \frac{1}{2}\pi_B^{S*}) + \frac{1+\lambda}{2}[(\pi_B^{S*} + (1 - \pi_B^{S*})\pi_A^{S*})][V(2) - 1] - c(\pi_A^{S*}), \\ W_B(S_l, S_l) &= \pi_B^{S*}(1 - \frac{1}{2}\pi_A^{S*}) + \frac{1-\lambda}{2}[(\pi_A^{S*} + (1 - \pi_A^{S*})\pi_B^{S*})][V(2) - 1] - c(\pi_B^{S*}) \text{ and} \\ W_i(S_l, S_k) &= \pi_l^{D*} - c(\pi_l^{D*}). \end{aligned}$$

Now denote $V(2)$ by $V(2)^*_{RA}$ such that

$$W_i((S_l, S_l); V(2)^*_{RA}, \lambda = 0) = W_i(S_l, S_k) \text{ where}$$

$$W_i((S_l, S_l); V(2)^*_{RA}, \lambda = 0) = \frac{1}{2}\{(\pi_i^{S*} + \pi_j^{S*})[V(2)^*_{RA} + 1] - (\pi_i^{S*}\pi_j^{S*})V(2)^*_{RA}\}.$$

According to Lemma 3, whenever $V(2) > V(2)^*_{RA}$, the first mover finds it optimal to form the research alliance and capture the network value of R&D success by offering low enough λ to the firm B. Then, the equilibrium in the research alliance game is summarized in Proposition 9.

Proposition 9 *In the subgame perfect Nash equilibrium of the research alliance game,*
(1) if compatibility externality is big enough that $V(2) \geq V(2)^*_{RA}$*, then firms form a research alliance in the first stage and exert* π_i^{S*} *with* $i \in \{A, B\}$ *for some* $\lambda \in [0, 1]$ *in the second stage.*
(2) if compatibility externality is small enough that $V(2) < V(2)^*_{RA}$*, then firms choose different sites in the first stage and exert* π^{D*} *in the second stage.*

Proof. See the Appendix. ■ Now, we have the following result on the relation between $V(2)^{**}$ and $V(2)^*_{RA}$.

Lemma 4 *For given* $c(\cdot)$*,* $V(2)^*_{RA}$ *is strictly smaller than* $V(2)^{**}$*.*

Proof. See the Appendix. ■ Accordingly, we have the following excess duplication result on the equilibrium site choice of the research alliance game.

Proposition 10 *(**Excess Duplication**) In the research alliance game, the equilibrium exhibits the following inefficiencies.*
(1) For $V(2)$ *with* $V(2)^*_{RA} \leq V(2) < V(2)^{**}$*, the firms choose the same site too much and both firms make over-investment for low enough* λ*.*
(2) For $V(2)$ *with* $V(2)^{**} < V(2) < V(2)^*_{BR}$*, the firms' choosing the same site is efficient, but the firms make over-investment for low enough* λ*.*
(3) For $V(2)$ *with* $V(2) > V(2)^*_{BR}$*, firm's choosing the same site is efficient, but the firms make under-investment for low enough* λ*.*

Proof. See the Appendix. ■

Note that the first and the second result of Proposition 20 resemble the result of excess duplication and excessive effort in the equal sharing R&D game. But, the third result of Proposition 20 is in contrast to the excessive effort result in the equal sharing R&D game and also in contrast to the typical result of over-investment which has been found in most R&D literature such as Loury(1979) and Reinganum(1980). The under-investment result follows from the characteristics of the payoff structure of the research alliance in which firms have incentive for free-riding on each other's investment since they share the network value of the R&D success even when the rival is the sole discoverer.

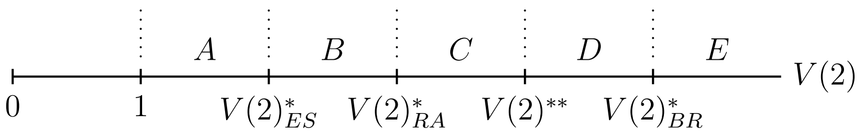

Figure 5: Ordering of compatibility externality thresholds in each game

6 Policy Implications on Standardization

Since compatibility externality isn't often internalized in firms' private incentive, thereby resulting in inefficient allocations, most of research on compatibility externality has suggested a certain type of intervention of government agency to reduce such inefficiency. Few literature, however, has dealt with the effect of public policy on firms' R&D project choice with compatibility externality. In this section, the effects on equilibria in each noncooperative game of the various public policy devices are reviewed and the efficacy of each policy is discussed with a regard to a standard-setting issue.

Consider first Corollary 2 in which the thresholds of compatibility externality in each game and that of the social planner are compared and put in order, which are shown in Figure 5.

Corollary 2 *The threshold of compatibility externality in each game is ordered as follows.*

$$V(2)^*_{ES} < V(2)^*_{RA} < V(2)^{**} < V(2)^*_{BR}.$$

Proof. See the Appendix. ■

In the following, we consider the various cases each of which corresponds to each range in Figure 5. Recall that since the effort level(or the probability of success in each site) contributes the increase of the expected payoff from R&D success and incurs R&D activity cost, it can be considered as investment. So both efforts and investments are used interchangeably in this section. Similarly, sites and standards are used interchangeably in this section.

The region A - the case that $1 < V(2) < V(2)^*_{ES}$

In this case, firms choose different standards in all the 3 games, which is efficient. Moreover, since the equilibrium investment level conditional on differentiation is also efficient, no efficiency problem arises when compatibility externality is small enough as in the region A. Hence, there's no need for intervention of government agency for standardization, and the multiple standard regime in which firms are free to develop products based on different incompatible standards is desirable. On the contrary, a mandatory single standard regime which might be implemented with over estimation of compatibility externality, lowers the social welfare by making foregone the chance of additional innovation.

The region B - the case that $V(2)^*_{ES} < V(2) < V(2)^*_{RA}$

In this case, if the relevant industry situation is close to the one characterized by the Bertrand R&D game or by the research alliance game, then firms will choose different standards, which is efficient. But, if the relevant industry situation is close to the one characterized by the equal sharing R&D game, firms will choose the same standard, which is inefficient.

Since the equilibrium investment level conditional on duplication is inefficiently high in the equal sharing R&D game as proven in Double Inefficiency Proposition (Proposition 7), the policy intervention promoting differentiation could substantially increase the social welfare when the payoff structure of the relevant industry is closed to that of the equal sharing R&D game. Consider the case in which instant mimicking is easily attained and it's profitable to entrants, which implies that the simultaneous discovery doesn't dissipate all the reward from R&D success. In such case, if the second mover's choosing the same standard occurs due to weak protection of fundamental technologies, more strict implementation of IPR protection policy on fundamental technologies would induce the second mover to choose another standard, which relieves the problem of excess duplication problem and thereby excess investment problem as well. Also one can think of the case that firms seek a single standard with the expectation that they can manage to collude and refrain from fierce competition in the event that both firms succeed in R&D at the same time. In such case, per-unit investment tax which is imposed on marginal revenue from increase in investment conditional on duplication may also reduce the incentive to duplicate standard choice.[34]

[34] For example, τ of per-unit investment tax reduces the firms' marginal revenue from increase in investment from $(1 - \frac{1}{2}\pi)V(2)$ to $(1 - \frac{1}{2}\pi - \tau)V(2)$ in the equal sharing R&D game. Since the excess duplication result occurs due to the over-rewarded marginal revenue conditional on duplication, firms has less incentive to duplicate standard choice in the first

The region C - the case that $V(2)^*_{RA} < V(2) < V(2)^{**}$

In this case, if the relevant industry situation is close to the one characterized by the equal sharing R&D game or by the research alliance game, firms may choose the same standard, which is inefficient. The excess duplication and the over-investment problem arises as in the case of the region B, so the policy intervention promoting differentiation described in the previous case such as more strict implementation of IPR protection policy or per-unit investment tax can be implemented to increase the social welfare.

If the relevant industry situation is close to the one characterized by the Bertrand R&D game, then firms choose different standards, which is efficient.

The region D - the case that $V(2)^{**} < V(2) < V(2)^*_{BR}$

In this case, if the payoff structure of the relevant industry is closer to that of the Bertrand R&D game, there may arise excess differentiation in firms' standard choice. If the payoff structure of the relevant industry is closer to that of the equal sharing R&D game or that of the research alliance game, then firms choose the same standard in the equilibrium, which is efficient. Then, the inefficiency involved in standard choice in the Bertarnd R&D game can be easily reduced by establishing the mandatory single standard regime. Moreover, especially in the industries characterized by the Bertrand payoff structure, the equilibrium investment level given duplication is also efficient. So, all the inefficiency problem is completely resolved with the mandatory single standard regime. But, recall that the sum of firms' expected payoff conditional on duplication is lower than that of the social planner. So, the social planner may need to compensate for their possible ex ante loss from simultaneous discovery. Hence, alternatively, the lump-sum subsidy for firms choosing a particular standard may be implemented to increase the firms' incentive for duplication, thereby decrease excess duplication problem.[35] The subsidy should be of a lump-sum form so that it won't distort efficient investment incentive structure given duplication in the Bertrand R&D game.

In the industries which can be captured by the equal sharing R&D game, even though firms' standard choice is efficient, the equilibrium investment

stage.

[35] In the current model, both sites are ex ante complectly identical. But, if sites are asymmetric and one site is better than the other in terms of the first-order or the second-order stochastic dominance, then the lump-sum subsidy should be given to the firms choosing the better site.

level given duplication is too high. The excess equilibrium investment problem may be relieved by introduction of per-unit investment tax as discussed in the previous cases unless it causes the firms' after tax marginal investment revenue to get smaller than that of the social planner. However, the strict implementation of IPR protection policy should not be used since it may induce the second firm to choose different standard, which might result in excess differentiation.

In the industries which can be captured by the research alliance game, firms' equilibrium investment level within a research alliance is inefficient even though duplication is the efficient standard choice. In this case, the intervention of government agency should be a mix of two different competition-fostering policies because the equilibrium in the research alliance game exhibits two types of inefficiencies each of which needs a separate policy intervention. First, note that the asymmetric inefficiency involved in investment choice worsens as the first mover's advantage is greater (λ is closer to 1). Since the first mover's footing in determining λ depends on how proprietary the fundamental technology the first mover has chosen is, a lenient IPR policy fundamental technologies could strengthen the second mover's footing in determining λ, thereby relieves the asymmetric inefficiency problem in investment choice. Second, the per-unit investment tax needs to be implemented in order to reduce firms' incentive for over-investment as discussed earlier. But, the per-unit investment tax should be minimal so that it won't induce firms to choose different standards.

The region E - the case that $V(2) > V(2)^*_{BR}$

In this case, firms choose the same standard in all the 3 games, which is efficient. In the Bertrand R&D game, the equilibrium investment level is efficient, so there's no need for any intervention of government agency.

But, in the equal sharing R&D game, excess investment problem remains, so the per-unit investment tax needs to be imposed to reduce firms private incentive for investment down to the level of the social planner's incentive for investment.

In the research alliance game, asymmetric inefficiency problem needs another policy mix : a lenient IPR policy on fundamental technologies and per-unit investment subsidy. The lenient IPR policy can be used to reduce asymmetric inefficiency as discussed before. Now recall that firms' incentive for investment in the research alliance is smaller than that of the social planner for all $V(2)$ with $V(2) > V(2)^*_{BR}$ when both firms equally split the network value of R&D success(Claim 3). Hence, the per-unit investment subsidy which increase firms' marginal revenue up to that of the social planner would reduces inefficiency arising from under-investment.

7 Discussions

7.1 Single standard regime vs. Multiple standard regime

In the section 6, we have reviewed how the inefficiency involved in standard choice and investment choice in each game can be relieved by several public polices. But, if the information on the magnitude of compatibility externality and the payoff structure of the relevant industry is not available, then what the optimal policy mix is would not be clear.

Especially, establishing the mandatory single standard regime could be risky in that it might preclude the chance of another innovation, which could decrease social welfare in the case that $V(2) < V(2)^{**}$.[36] The case that the mandated single standard regime may increase social welfare is that the relevant market is very competitive, so close to the Bertrand R&D game and compatibility externality falls down to the region D. In that case, the mandated single standard regime can reduce inefficiency from excess duplication and no other policy device is needed. However, if the relevant market is close to the case of the equal sharing R&D game and the research alliance game, over or under investment arises due to the discrepancy between firms' incentive for investment and that of the social planner in the equal sharing R&D game and the research alliance game. Since such inefficiencies still remain in the mandated single standard regime, other policy devices should be implemented to reduce inefficiencies involved in investment choice.[37]

Now consider the market based multiple standard regime. With the market based multiple standard regime, there's no loss involved in preclusion of another innovation. But, if the relevant market is close to that of the Bertrand R&D game and the size of compatibility externality falls in the region of D, then there may arise excess differentiation. No inefficiency prob-

[36] See the cases of the region A,B,C.

[37] If the government is interested in the amount of output rather than social welfare, for example, in the arms-race, then the over-investment in the equal sharing R&D game and the research alliance game may not be a critical issue, so no other policy tool is needed.

lem involved in investment choice arises in the market which is close to that of the Bertrand R&D game. But, if the relevant market is close to the case of the equal sharing R&D game or the research allaince game, then inefficiencies involved in investment choice arise, which can be reduced only by implementation of other policy tools.

Now consider the example of the second generation wireless telecommunication market in the US and the European countries where the European countries have adopted the mandated single standard regime and the US has adopted the market based multiple standard regime. Given that it is probable that the second generation wireless telecommunication market could be very competitive, if compatibility externality is expected to be big enough, then it would be reasonable to choose the mandated single standard regime, which seems to be the reason for the European countries's choice of the mandated single standard regime. On the contrary, if compatibility externality is not substantial or the cost of constructing an adaptor is not so big, then the reasonable standard regime is the market based multiple standard regime as in the case of the US.[38] The size of the compatibility externality depends on the size of the market. But according to Gandal & Salant(2003), the cost of constructing an adaptor is not so big, so the market-based multiple standard regime has more benefits, which supports the US choice of the market based multiple standard regime. Moreover, even when the cost of constructing an adaptor is big enough, the inefficiencies from excess differentiation can be reduced with the market based multiple standard regime by implementing a lump-sum investment subsidy, while any other policy instrument can't make up for the loss of foregone innovation with the mandated single standard regime.

7.2 Ex post standardization with costly adapter

One of the main assumption in the model is that compatibility can be attained only through choosing the same standard, so prospect products from different standards are incompatible. It means that compatibility decision can be made only ex ante and making products from different standard compatible ex post is too costly, so virtually impossible. But, in some cases, installing adapters incurs only some reasonable cost, so originally incompatible products may become compatible with adapters. Then, compatibility can

[38]The issue related to constructing an adaptor is discussed in the next subsection.

be obtained both through duplication and through differentiation. However there are two main differences between the two ways. The first difference lies in what risk or cost firms should take besides R&D activity cost when firms want their products compatible. When firms choose to make their products compatible through duplication in site choice, then the firms bear the risk of possible loss from simultaneous discovery. If firms choose to make their products compatible through differentiation in site choice followed by construction of an adapter, then firms don't have to bear the risk of simultaneous discovery but they have to incur the cost of installing adapter after the development of products. The second difference lies in the timing of standardization. When firms choose the same site, then standardization is achieved ex ante, while standardization is achieved ex post when firms choose different sites and construct an adapter after the development of products. Now consider firms' expected payoff following differentiation which is

$$W_i((S_l, S_k); V(2), A) = \pi_i[V(2) - A] - c(\pi_i)$$

where A is the cost of installing adaptor. Note that $W_i((S_l, S_k); V(2), A)$ increases by π_i for the marginal increase in $V(2)$, while $W_i((S_l, S_l); V(2))$ increases by $\pi_i(1 - \pi_i)$ for the marginal increase in $V(2)$ in the Bertrand R&D game. Hence, it follows that ex post standardization is more attractive compared to ex ante standardization as compatibility externality is bigger because the cost of constructing a adapter is independent of compatibility externality while the value of expected loss from simultaneous discovery is increasing in compatibility externality. Then, the equilibrium site choice is monotone as Proposition 2 in the main model. But the direction is opposite.

Since there remains the discrepancy between firms incentive for investments and that of the social planner, inefficiency in effort choice still remains accordingly in the equal sharing R&D game and the research alliance game. So it does with the firms' standard choice, too. Therefore the most of the results in the main model also hold in the model where ex post standardization is available.

8 Conclusion

We build a simple static model in which two firms compete in R&D race in two stages for new generation technologies where two different R&D avenues are available, each being for different technologies incompatible with each other. Existence of compatibility gives firms an incentive to choose a single standard. But the possibility of simultaneous discovery gives firms an incentive to choose different standards. The interplay of the two incentives result in discrepancy between firms' private incentive and the social planner's incentive in both site choice problem and effort choice problem, the detail of which depends on how R&D reward is dissipated in the case of simultaneous discovery. In the Bertrand R&D game, firms' equilibrium site choice may exhibit excess differentiation, but the equilibrium effort choice is optimal. In the equal sharing R&D game, for some set of compatibility externality, there occurs double inefficiency problem with which firms choose the same site too much and make too much investments in the equilibrium. In the research alliance game, firms equilibrium site choice may exhibit too much differentiation and the equilibrium effort choice may be insufficient.

The interesting extensions of our model are as follows. First, a multi-period model which may capture firms' dynamic behavior, can be considered where there exists positive possibility that the treasure may not be buried in the site. With such probability of no treasure, firms R&D may end up with failure even when they make maximum investments. In that case, firms should form a belief on each site's having a treasure, which should be updated every period based on observation of the result of other firms' R&D experiment on each site. Second, in our model, the probability of success is assumed to be determined by the R&D activity cost without uncertainty. But one can consider the model with uncertainty in the way that the R&D activity cost determines not the probability of success itself, but its distribution.

Appendix

Proof of Claim 1

Proof. Consider Figure 6 in which $V(2)'' < V(2)^*_{BR} < V(2)'$. Since $c'(\cdot)$ is increasing in π_i, it follows that $\pi_i^{S*}(V(2)'') < \pi_i^{D*} < \pi_i^{S*}(V(2)')$. Since the case shown in Figure 6 can be generalized for all $V(2)$, it follows that π_i^{S*} is strictly increasing in $V(2)$. Therefore, $V(2) > V(2)^*_{BR}$ if and only if $\pi_i^{S*} > \pi_i^{D*}$. Equivalently, $V(2) < V(2)^*_{BR}$ if and only if $\pi_i^{S*} < \pi_i^{D*}$. ■

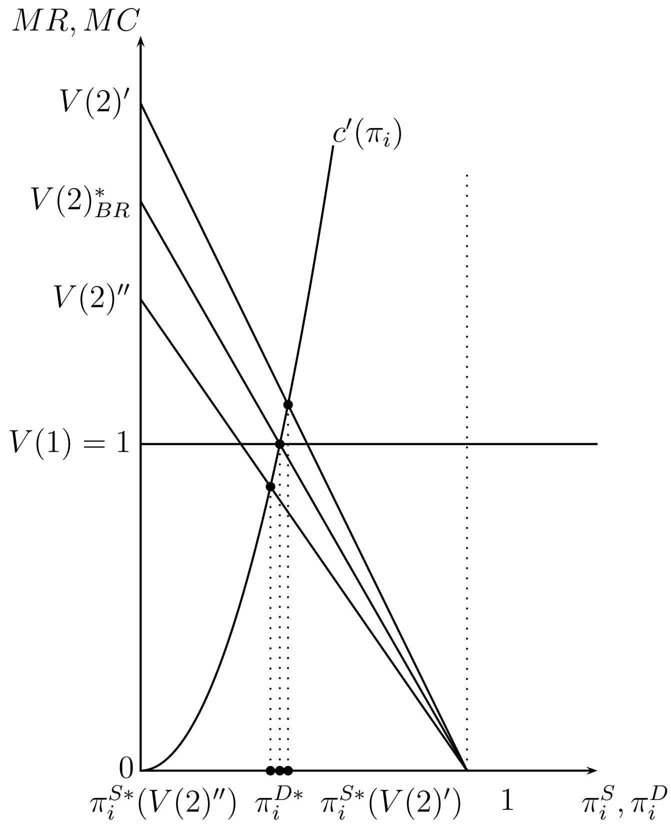

Figure 6: $\pi_i^{S*}(V(2)'') < \pi_i^{D*} < \pi_i^{S*}(V(2)')$

Proof of Proposition 2

Proof. Suppose the firm A chooses the site S_1 first. Given the firm A's site choice, the firm B receives

$$W_B(S_1, S_1) = \pi_1^{S*}(1 - \pi_1^{S*})V(2) - c(\pi_1^{S*}) \text{ by choosing the same site } S_1$$

$$\text{and } W_B(S_1, S_2) = \pi_2^{D*} - c(\pi_2^{D*}) \text{ by choosing the different site } S_2.$$

Now suppose $V(2) = V(2)^*_{BR}$. Then, since $\pi_1^{S*} = \pi_1^{D*}$ iff $V(2) = V(2)^*_{BR}$,

$$W_B((S_1, S_1); V(2)^*_{BR}) \quad = \quad \pi_1^{S*}(1 - \pi_1^{S*})V(2) - c(\pi_1^{S*})$$

$$
\begin{aligned}
&= \pi_1^{S*}(1-\pi_1^{S*})\frac{1}{1-\pi_1^{D*}} - c(\pi_1^{S*}) \\
&= \pi_1^{D*}(1-\pi_1^{D*})\frac{1}{1-\pi_1^{D*}} - c(\pi_1^{D*}) \\
&= \pi_1^{D*} - c(\pi_1^{D*}) \\
&= \pi_2^{D*} - c(\pi_2^{D*}) \\
&= W_B(S_1, S_2).
\end{aligned}
$$

The fifth equality comes from symmetry between sites. Now, recall that $W_i(S_l, S_l)$ with $S_l \in \{S_1, S_2\}$, the firm i's expected payoff conditional on duplication is increasing in $V(2)$, while $W_i(S_l, S_k)$, the firm i's expected payoff conditional on differentiation is independent of $V(2)$. Therefore, the firm B chooses the same site chosen by the firm A for all $V(2)$ with $V(2) > V(2)^*_{BR}$ in the equilibrium. Similarly, the firm B chooses the different site for all $V(2)$ with $V(2) < V(2)^*_{BR}$ in the equilibrium. The proof of the firms' optimal effort level given site choice is provided already in the body text. ■

Proof of Proposition 3

Proof. Note that by construction of $V(2)^{**}$, $W((S_l, S_l), V(2)^{**}) = W(S_1, S_2)$. Since $W((S_l, S_l), V(2))$ is increasing in $V(2)$, duplication is efficient for $\forall$ (2) with $V(2) > V(2)^{**}$, while differentiation is efficient for $\forall$ $V(2)$ with $V(2) < V(2)^{**}$.

By definition of π^{D**} and π^{S**}, they should be the optimal effort level given site choice, as shown in the body text. ■

Proof of Lemma 1

Proof. First, we show that $W((S_l, S_l); V(2)^*_{BR}) > W(S_1, S_2)$. Note that

$$
\begin{aligned}
W((S_l, S_l); V(2)^*_{BR}) &= \pi^{S**}(2-\pi^{S**})V(2)^*_{BR} - 2c(\pi^{S**}) \\
&= \pi^{S*}(2-\pi^{S*})V(2)^*_{BR} - 2c(\pi^{S*}) \\
&= \pi^{D*}(1-\pi^{D*})V(2)^*_{BR} + \pi^{D*}V(2)^*_{BR} - 2c(\pi^{D*}) \\
&= \pi^{D*} + \pi^{D*}V(2)^*_{BR} - 2c(\pi^{D*}) \\
&= \pi^{D*}[1 + V(2)^*_{BR}] - 2c(\pi^{D*}) \\
&> 2\pi^{D*} - 2c(\pi^{D*}) \\
&= 2\pi^{D**} - 2c(\pi^{D**}) \\
&= W(S_1, S_2).
\end{aligned}
$$

The second and the sixth equality follow from Proposition 1 that $\pi^{S**} = \pi^{S*}$ and $\pi^{D**} = \pi^{D*}$ for given $V(2)$. The third equality follows from the fact that $\pi^{S*} = \pi^{D*}$ iff $V(2) = V(2)^*_{BR}$. The fourth equality follows from the fact that $(1 - \pi^{D*})V(2)^*_{BR} = (1 - \pi^{D*})\frac{1}{(1-\pi^{D*})} = 1$.

Then, since $W((S_l, S_l), V(2))$ is increasing and continuous in $V(2)$, there exists $V(2)^{**}_{BR}$ such that $W((S_l, S_l), V(2)^{**}_{BR}) = W(S_1, S_2)$ and $V(2)^{**}_{BR} < V(2)^*_{BR}$. Since $V(2)^{**}$ is unique given the strictly convex cost function, it follows that $V(2)^{**}_{BR} = V(2)^{**}$, which completes the proof. $\blacksquare$

Proof of Proposition 4

Proof. According to Lemma 1, $[V(2)^{**}, V(2)^*_{BR}] \neq \emptyset$. Then, for $\forall\ V(2) \in [V(2)^{**}, V(2)^*_{BR}]$, $W((S_l, S_l), V(2)) > W(S_1, S_2)$, so the firms should duplicate site choice in the social optimum. But $W_i((S_l, S_l), V(2)) > W_i(S_1, S_2)$ for $\forall\ V(2) \in [V(2)^{**}, V(2)^*_{BR}]$. Therefore, the equilibrium site choice exhibits excess differentiation for $\forall\ V(2) \in [V(2)^{**}, V(2)^*_{BR}]$. $\blacksquare$

Proof of Claim 1

Proof. Consider Figure 6 in which $V(2)'' < V(2)^*_{ES} < V(2)'$. Since $c'(\cdot)$ is increasing in π_i, it follows that $\pi_i^{S*}(V(2)'') < \pi_i^{D*} = \pi_i^{S*}(V(2)^*_{ES}) < \pi_i^{S*}(V(2)')$. Since the case shown in the Figure can be generalized for all $V(2)$, it follows that π_i^{S*} is strictly increasing in $V(2)$. Therefore, $V(2) > V(2)^*_{ES}$ if and only if $\pi_i^{S*} > \pi_i^{D*}$. Equivalently, $V(2) < V(2)^*_{ES}$ if and only if $\pi_i^{S*} < \pi_i^{D*}$. $\blacksquare$

Proof of Proposition 6

Proof. Suppose the firm A chooses the site S_1 first. Given the firm A's site choice, the firm B receives

$$W_B(S_1, S_1) = \frac{1}{2}\pi_1^{S*}(2 - \pi_1^{S*})V(2) - c(\pi_1^{S*}) \text{ by choosing the same site } S_1$$

$$\text{and } W_B(S_1, S_2) = \pi_2^{D*} - c(\pi_2^{D*}) \text{ by choosing the different site } S_2.$$

Now suppose $V(2) = V(2)^*_{ES}$. Then, since $\pi_1^{S*} = \pi_1^{D*}\ iff\ V(2) = V(2)^*_{ES}$ in the equal sharing R&D game,

$$W_B((S_1, S_1), V(2)^*_{ES}) \;=\; \frac{1}{2}\pi_1^{S*}(2 - \pi_1^{S*})V(2)^*_{ES}) - c(\pi_1^{S*})$$

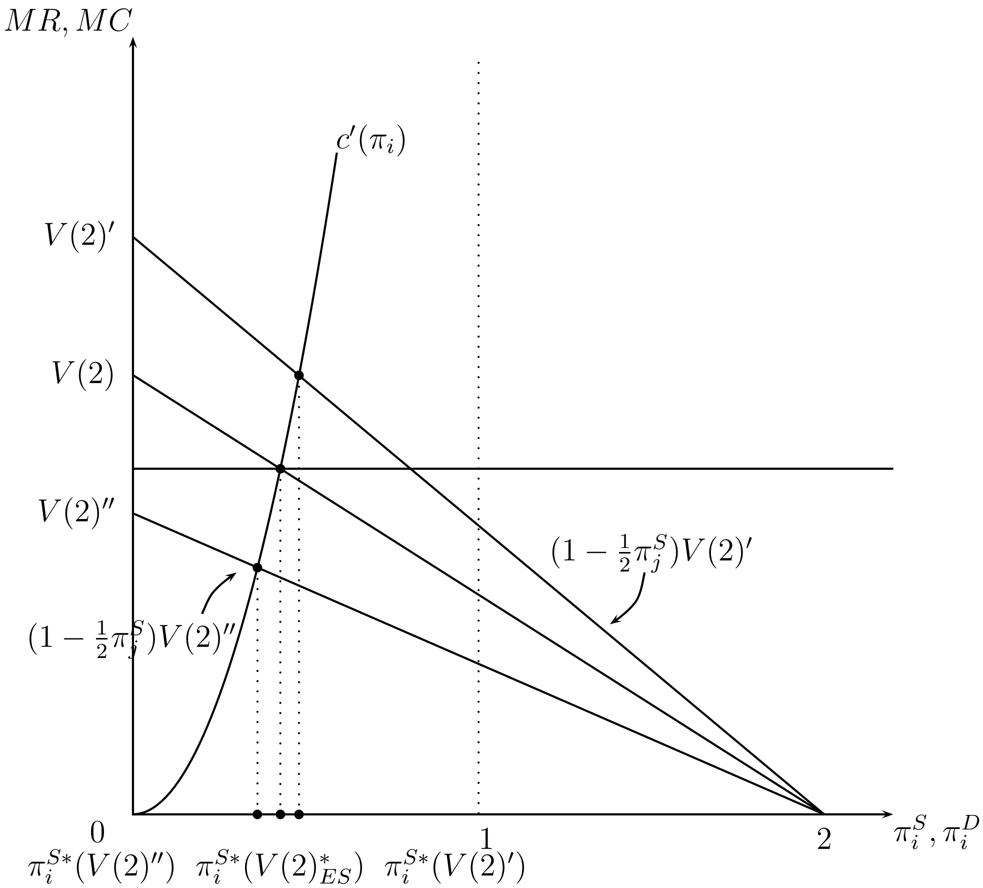

Figure 7: $\pi_i^{S*}(V(2)'') < \pi_i^{S*}(V(2)^*_{ES}) < \pi_i^{S*}(V(2)')$

$$
\begin{aligned}
&= \frac{1}{2}\pi_1^{S*}(2-\pi_1^{S*})\frac{1}{1-\frac{1}{2}\pi_1^{D*}} - c(\pi_1^{S*}) \\
&= \pi_1^{D*}(1-\frac{1}{2}\pi_1^{D*})\frac{1}{1-\frac{1}{2}\pi_1^{D*}} - c(\pi_1^{D*}) \\
&= \pi_1^{D*} - c(\pi_1^{D*}) \\
&= \pi_2^{D*} - c(\pi_2^{D*}) \\
&= W_B(S_1, S_2).
\end{aligned}
$$

Hence, by the same logic we used in the proof of Proposition 2, one can see that the firm B chooses the same site chosen by the firm A for all $V(2)$ with

$V(2) > V(2)^*_{ES}$ in the equilibrium. Similarly, the firm B chooses the different site for all $V(2)$ with $V(2) < V(2)^*_{ES}$ in the equilibrium. The proof of the result on firms' optimal effort level given site choice is provided in the proof of Claim 1. ■

Proof of Lemma 2

Proof. First, we show that $W((S_l, S_l), V(2)^*_{ES}) < W(S_l, S_k)$. Note that

$$\begin{aligned}
W((S_l, S_k)) &= W_1((S_l, S_l); V(2)^*_{ES}) + W_2((S_l, S_l); V(2)^*_{ES}) \\
&= [\pi_1^{S*}(1 - \pi_2^{S*}) + \frac{1}{2}\pi_1^{S*}\pi_2^{S*}]V(2)^*_{ES} - c(\pi_1^{S*}) \\
&+ [\pi_2^{S*}(1 - \pi_1^{S*}) + \frac{1}{2}\pi_2^{S*}\pi_1^{S*}]V(2)^*_{ES} - c(\pi_2^{S*}) \\
&> [\pi^{S**}(1 - \pi^{S**}) + \frac{1}{2}\pi^{S**}\pi^{S**}]V(2)^*_{ES} - c(\pi^{S**}) \\
&+ [\pi^{S**}(1 - \pi^{S**}) + \frac{1}{2}\pi^{S**}\pi^{S**}]V(2)^*_{ES} - c(\pi^{S**}) \\
&= \pi^{S**}(2 - \pi^{S**})V(2)^*_{ES} - 2c(\pi^{S**}) \\
&= W((S_l, S_l), V(2)^*_{ES}).
\end{aligned}$$

The equalities in the first and the second line follow from the definition of $V(2)^*_{ES}$. The first inequality in the fourth line follows from Proposition 5 that $\pi^{S**} < \pi^{S*}$ for given $V(2)^*_{ES}$ and the fact that π^{S*} is the maximizer of the firms profit, not π^{S**}. The third equality comes from the definition of $V(2)^*_{ES}$.

Now recall that $W((S_l, S_k)) = W((S_l, S_l), V(2)^{**})$ by the definition of $V(2)^{**}$. Then, since $W((S_l, S_k)) > W((S_l, S_l), V(2)^*_{ES})$, it follows that

$$W((S_l, S_l), V(2)^{**}) > W((S_l, S_l), V(2)^*_{ES}).$$

Then, the monotonicity of $W((S_l, S_l), V(2))$ in $V(2)$ shows that $V(2)^{**} > V(2)^*_{ES}$, which completes the proof. ■

Proof of Proposition 7

Proof. According to Lemma 2, $[V(2)^*_{ES}, V(2)^{**}] \neq \emptyset$.
(1) For $\forall$ $V(2)$ with $V(2) > V(2)^{**}, W((S_l, S_l), V(2)) > W(S_1, S_2)$, so duplication in site choice in the equilibrium is efficient. But, the equilibrium

effort conditional on duplication is inefficiently high according to Proposition 5, so the equilibrium effort level given duplication is higher than in the social optimum although firms' site choice of duplication in the equilibrium is efficient.

(2) Then, for $\forall\ V(2) \in [V(2)^*_{ES}, V(2)^{**}], W((S_l, S_l), V(2)) < W(S_1, S_2)$, so the firms should differentiate site choice in the social optimum. But $W_i((S_l, S_l), V(2)) > W_i(S_1, S_2)$ for $\forall\ V(2) \in [V(2)^*_{ES}, V(2)^{**}]$. Therefore, the equilibrium site choice exhibits excess duplication for $\forall\, V(2) \in [V(2)^*_{ES}, V(2)^{**}]$. Moreover, again the equilibrium effort level conditional on duplication is inefficiently high according to Proposition 5. Therefore for $\forall\, V(2) \in [V(2)^*_{ES}, V(2)^{**}]$, the equilibrium exhibits both excess duplication and excess effort choice. ■

Proof of Claim 3

Proof. (1) For a bench mark, consider first the firms' expected payoffs conditional on forming a research alliance in the case with $\lambda = 1$ where

$$\begin{aligned}
W_A(S_l, S_l; V(2), \lambda = 1) &= \pi^S_A(1 - \pi^{S*}_B) + \pi^S_A(1 - \pi^{S*}_B)[V(2) - 1] - c(\pi^S_A) \\
&= \pi^S_A(1 - \pi^{S*}_B)V(2) - c(\pi^S_A) \text{ and} \\
W_B(S_l, S_l; V(2), \lambda = 1) &= \pi^S_B(1 - \pi^{S*}_A) - c(\pi^S_B).
\end{aligned}$$

Then, π^{S*}_i with $i \in \{A, B\}$, the firm i' equilibrium effort level with $\lambda = 1$ solves the following the first order conditions,

$$\begin{aligned}
(1 - \pi^{S*}_B)V(2) &= c'(\pi^{S*}_A) \text{ and} \\
(1 - \pi^{S*}_A) &= c'(\pi^{S*}_B).
\end{aligned}$$

Then, by comparing the left hand side of the first order conditions, one can see that π^{S*}_B, the firm B's equilibrium effort level is strictly smaller than π^{S*}_A, the firm A's equilibrium effort level.

Now recall that the social planner's effort choice problem conditional on both being at S_l is

$$Max_{\pi^S_A, \pi^S_B}\{[1 - (1 - \pi^S_A)(1 - \pi^S_B)]V(2) - c(\pi^S_A) - c(\pi^S_B)\},$$

and its corresponding first order condition is

$$(1 - \pi^{S**}_j)V(2) = c'(\pi^S_i) \text{ for } i, j \in \{A, B\} \text{ with } i \neq j.$$

Then, since $\pi_B^{S*} < \pi_A^{S*}$, it follows that $\pi_B^{S*} < \pi_B^{S**}$ and $\pi_A^{S*} > \pi_A^{S**}$.

Now, for another bench mark, consider the firms' expected payoffs conditional on forming a research alliance in the case with $\lambda = 0$ where

$$\begin{aligned}
W_A(S_l, S_l; V(2), \lambda = 0) &= \pi_A^S(1 - \pi_B^{S*}) + \frac{1}{2}\pi_A^S(1 - \pi_B^{S*})[V(2) - 1] - c(\pi_A^S) \\
&= \frac{1}{2}\pi_A^S(1 - \pi_B^{S*})[V(2) + 1] - c(\pi_A^S) \text{ and} \\
W_B(S_l, S_l; V(2), \lambda = 0) &= \pi_B^S(1 - \pi_A^{S*}) + \frac{1}{2}\pi_B^S(1 - \pi_A^{S*})[V(2) - 1] - c(\pi_B^S) \\
&= \frac{1}{2}\pi_B^S(1 - \pi_A^{S*})[V(2) + 1] - c(\pi_B^S).
\end{aligned}$$

Then, π_i^{S*} with $i \in \{A, B\}$, the firm i's equilibrium effort level with $\lambda = 0$ solves the following the first order conditions,

$$\frac{1}{2}(1 - \pi_j^{S*})[V(2) + 1] = c'(\pi_i^S) \text{ with } i \in \{A, B\} \text{ and } i \neq j.$$

Then, by comparing the left hand side of the first order conditions to those of the social planner's, one can see that $\pi_A^{S*} = \pi_B^{S*}$ with $\lambda = 0$ is strictly smaller than π^{S**}, the socially optimal effort level. Now note that the firm B's marginal revenue is decreasing in λ for given $V(2)$ both directly and indirectly in the following ways. First, increase in λ directly lowers the firm B's sharing portion of the extra reward from R&D success, which decreases the firm B's marginal revenue from increase in π_B^{S*}. Second, the increase in λ raises the firm A's marginal revenue from increase in its effort, which in turn, increase the firm A's equilibrium effort level. Since the increase in the firm A's equilibrium effort level reduces the probability of the firm B's exclusive discovery, the firm B's marginal revenue from increase in π_B^{S*} decreases accordingly. So, since the firm B's marginal revenue is decreasing in λ for given $V(2)$, and is smaller than the socially optimal level even when it has the maximum value as $\lambda = 0$, it follows that the second mover, the firm B's equilibrium effort level is strictly lower than the socially optimal level for all $\forall\ \lambda \in [0, 1]$.

Now, returning to π_A^{S*}, we have $\pi_A^{S*} > \pi_A^{S**}$ as $\lambda = 1$ and $\pi_A^{S*} < \pi_A^{S**}$ as $\lambda = 0$. Note that the firm A's marginal revenue is continuously increasing in λ and π_B^{S*} for given $V(2)$, so π_A^{S*} is continuously increasing in λ and π_B^{S*} for given $V(2)$ accordingly. But, since π_B^{S*} is continuously decreasing in λ, so for given $V(2)$, there exists $\lambda^*(V(2)) \in (0,1)$ such that $\pi_A^{S*} = \pi_A^{S**}$. Therefore, for given $V(2)$, π_A^{S*} is smaller than π_A^{S**} for $\forall\ \lambda < \lambda^*(V(2))$, while π_A^{S*} is greater than π_A^{S**} for $\forall\ \lambda > \lambda^*(V(2))$.

(2) The payoff structure in the case when firms differentiate site choice in the research alliance game is identical to that in the other two noncooperative games in the previous sections. So the efficiency result on the equilibrium effort level proven in the previous games also hold for the equilibrium effort level conditional on differentiation in the research alliance game. ■

Proof of Claim 6

Proof. (1) Fix $\lambda \in [0,1]$. Then, for given λ, if $V(2) = V(2)_{RA}(\lambda)$, then we have $(1-\pi_A^{S*}) + \frac{1-\lambda}{2}(1-\pi_A^{S*})[V(2)_{RA}(\lambda) - 1] = 1 = V(1)$ by definition, so the left-hand side of the first order conditions are identical. So, the right-hand side of the conditions, the marginal costs should be equal, by which the arguments of the marginal costs should be equal, too since marginal cost function is strictly convex. Hence we have $\pi_B^{S*} = \pi^{D*}$ if $V(2) = V(2)_{RA}(\lambda)$. Since the firm B's marginal revenue from increase in effort is increasing in $V(2)$, for given λ, $(1-\pi_A^{S*}) + \frac{1-\lambda}{2}(1-\pi_A^{S*})[V(2)_{RA}(\lambda) - 1] > V(1)$ for $\forall\ V(2)$ with $V(2) > V(2)_{RA}(\lambda)$, which results in $\pi_B^{S*} > \pi^{D*}$. By the same reason, for given λ we have $\pi_B^{S*} < \pi^{D*}$ for $\forall\ V(2)$ with $V(2) < V(2)_{RA}(\lambda)$ (2) Since the firm A's marginal revenue is greater than the firm B's for $\forall\ \lambda \in (0,1]$, it follows that π_A^{S*} is greater than π_B^{S*} for $\forall\ \lambda \in (0,1]$. ■

Proof of Proposition 8

Proof. (1) Suppose $V(2) > V(2)^*_{BR}$.

First, we prove $\pi_B^{S*} < \pi^{S**}$ for $\forall\ \lambda \in [0,1]$. Denote by $\pi_i^{S*}(\lambda)$ the firm i's equilibrium effort choice for given $V(2)$ and λ. According to Claim 3, if $V(2) > V(2)^*_{BR}$, then $\pi_i^{S*}(0) < \pi^{S**}$ for given $V(2)$ with $i \in \{A, B\}$. Since $\pi_B^{S*}(\lambda)$ is decreasing in λ, we have $\pi_B^{S*}(\lambda) < \pi^{S**}$ for $\forall\ \lambda \in [0,1]$ given $V(2)$ with $V(2) > V(2)^*_{BR}$.

Second, we prove $\pi_A^{S*}(\lambda)$ may be higher or lower than π^{S**}, depending on λ for given $V(2)$ with $V(2) > V(2)^*_{BR}$. For the case with $\lambda = 0$, we have $\pi_A^{S*}(0) < \pi^{S**}$ according to Claim 3. Now, consider the case with $\lambda = 1$, where the firm A's marginal effort revenue is $(1 - \frac{1}{2}\pi_B^{S*}(1)) + \frac{1+\lambda}{2}(1 - \pi_B^{S*}(1))[V(2) - 1]$ which boils down to $(1 - \pi_B^{S*}(1))V(2) + \frac{1}{2}\pi_B^{S*}(1)$. So, since $\pi_B^{S*}(1) < \pi^{S**}$, the firm A's marginal revenue from increase in π_A^S is greater than $(1-\pi_B^{S**})V(2)$, the social planner's marginal revenue from increase in π_A^S, thereby we have $\pi_A^{S*}(1) > \pi^{S**}$. Hence, we have $\pi_A^{S*}(0) < \pi^{S**}$ and $\pi_A^{S*}(1) > \pi^{S**}$. Then, given that $(1-\frac{1}{2}\pi_B^{S*}) + \frac{1+\lambda}{2}(1-\pi_B^{S*})[V(2)-1]$ is continuously increasing in λ, there exists some $\lambda' \in (0,1)$ for given $V(2)$ with $V(2) > V(2)^*_{BR}$ such that $\pi_A^{S*}(\lambda') = \pi^{S**}$. Therefore, for given $V(2)$ with $V(2) > V(2)^*_{BR}$, we have $\pi_A^{S*}(\lambda) \geq \pi^{S**}$ if and only if $\lambda \geq \lambda'$, which completes the proof.

(2) First consider $\pi_A^{S*}(\lambda)$. According to Claim 3, $\pi_A^{S*}(0) > \pi^{S**}$ if $V(2) \in [V(2)^*_{RA}, V(2)^*_{BR})$. Moreover, the firm A's marginal revenue from increase in π_A is increasing in λ, so we have $\pi_A^{S*}(\lambda) > \pi^{S**}$ for $\forall\ \lambda \in [0,1]$.

Next, consider $\pi_B^{S*}(\lambda)$. If $\lambda = 0$, then we have $\pi_B^{S*}(0) > \pi^{S**}$ for $V(2) \in [V(2)^*_{RA}, V(2)^*_{BR})$ according to Claim 3. Since the firm B's marginal revenue from increase in π_B is continuously decreasing in λ, it follows that $\pi_B^{S*}(\lambda) > \pi^{S**}$ for λ close to 0 when $V(2) \in [V(2)^*_{RA}, V(2)^*_{BR})$. Now recall that $\pi_B^{S*}(0) = \pi^{S**}$ when $V(2) = V(2)^*_{BR}$. Then, since the firm B's marginal revenue from increase in π_B is continuously decreasing in λ, it follows that $\pi_B^{S*}(\lambda) < \pi^{S**}$ for $\lambda > 0$. Since the firm B's marginal revenue from increase in π_B is continuous in $V(2)$, so it still holds that $\pi_B^{S*}(\lambda) < \pi^{S**}$ for big enough λ even when $V(2) < V(2)^*_{BR}$. Therefore, $\pi_B^{S*}(\lambda)$ can be lower or higher than π^{S**} depending on λ and $V(2)$, which completes the proof. ■

Proof of Lemma 3

Proof. First we prove for necessity. Suppose that firms choose the same site in the equilibrium where $W_B(S_l, S_l; V(2), \lambda = 0) < W_B(S_l, S_k)$. But, given that $W_B(S_l, S_l; V(2), \lambda = 0) < W_B(S_l, S_k)$ and the firm A can't offer λ strictly smaller than 0, the firm B finds it strictly better to choose a different site rather than accepting the firm A's offer of $\lambda = 0$. Therefore, if firms choose the same site in the equilibrium, then it should be that

$$W_B(S_l, S_l; V(2), \lambda = 0) \geq W_B(S_l, S_k).$$

Next, we prove for sufficiency. Since

$$W_A(S_l, S_l; V(2), \lambda = 0) = W_B(S_l, S_l; V(2), \lambda = 0) \text{ and } W_A(S_l, S_k) = W_B(S_l, S_k),$$

$$\text{we have } W_A(S_l, S_l; V(2), \lambda = 0) \geq W_A(S_l, S_k),$$
$$\text{whenever } W_B(S_l, S_l; V(2), \lambda = 0) \geq W_B(S_l, S_k).$$

Specifically, consider the case that $W_B(S_l, S_l; V(2), \lambda = 0) > W_B(S_l, S_k)$. Then, since $W_i(S_l, S_l; V(2), \lambda)$ with $i \in \{A, B\}$ is continuous in λ for given $V(2)$, there exists some $\lambda'' \in (0, 1]$ such that $W_A(S_l, S_l; V(2), \lambda'') > W_A(S_l, S_k)$ and $W_B(S_l, S_l; V(2), \lambda'') > W_B(S_l, S_k)$ for given $V(2)$, which completes the proof. ■

Proof of Claim 5

Proof. Let $\lambda = 0$. Then, the expected payoff of the firm i with $i \in \{A, B\}$ from forming a research alliance is

$$W_i(S_l, S_l; V(2), \lambda = 0) = [\pi_i(1-\pi_j^{S*})+\frac{1}{2}\pi_i\pi_j^{S*}]+\frac{1}{2}[\pi_j^{S*}+(1-\pi_j^{S*})\pi_i][V(2)-1]-c(\pi_i).$$

Then, the first order condition with respect to π_i boils down to

$$\frac{1}{2}[(1-\pi_j^{S*})V(2)+1] = c'(\pi_i).$$

Now compare the firm i's marginal revenue from increase in the effort(the left hand side of the first order condition) to that of the social planner which is $(1-\pi_j^{S**})V(2)$. Both the social marginal revenue and the private marginal revenue are monotonic in $V(2)$, so the equilibrium effort levels also are monotonic in $V(2)$. Now let $V(2) = V(2)^*_{BR} = \frac{1}{1-\pi_j^{D*}}$. Then, the social marginal revenue from increase in the firm i's effort becomes 1 which is the firms' marginal revenue conditional on differentiation according to Claim 1. The firms' private marginal revenue also becomes $\frac{1}{2}[(1-\pi_j^{S*})\frac{1}{1-\pi_j^{D*}}+1]$ which is strictly greater than 1 if and only if $\pi_j^{D*} > \pi_j^{S*}$. But, if $\pi_j^{D*} > \pi_j^{S*}$ so that the firms' marginal revenue conditional on forming a research alliance is greater than that conditional on differentiation, it should follow that $\pi_j^{D*} < \pi_j^{S*}$ which is contradiction to the supposition. By the same reason, it can't be strictly smaller than 1. So it follows that when $V(2) = V(2)^*_{BR}$, the firms' marginal revenue conditional on forming a research alliance should be exactly 1, which is the same as that of the social planner. Now note that the firms' marginal revenue is increasing in $V(2)$ at the rate of $\frac{1}{2}(1-\pi_j^{S*})$, while that of the social planner is increasing in $V(2)$ at the rate of $(1-\pi_j^{S*})$. Then, since $\pi_i^{S*} = \pi_i^{S**}$ as $V(2) = V(2)^*_{BR}$, so it follows that $\pi_i^{S*} > \pi_i^{S**}$ for all $V(2)$ with $V(2)^*_{RA} < V(2) < V(2)^*_{BR}$. Similarly, $\pi_i^{S*} < \pi_i^{S**}$ for all $V(2)$ with $V(2) > V(2)^*_{BR}$. ■

Proof of Proposition 9

Proof. Since $W_i(S_l, S_l); V(2), \lambda = 0)$ is increasing in $V(2)$, $W_i(S_l, S_l); V(2), \lambda = 0) \geq W_i((S_l, S_l); V(2)^*_{RA}\lambda = 0)$ for all $V(2)$ with $V(2) \geq V(2)^*_{RA}$ by the definition of $V(2)^*_{RA}$. Hence, according to Lemma 3, both firms prefer to form a research alliance if and only if $V(2) \geq V(2)^*_{RA}$. The proof of firms equilibrium effort choice is provided in the proof of Proposition 8. ■

Proof of Lemma 4

Proof. Recall that

$$W_i((S_l, S_l); V(2), \lambda = 0) = [\pi_i^{S*}(1-\pi_j^{S*})+\frac{1}{2}\pi_i^{S*}\pi_j^{S*}]+\frac{1}{2}[\pi_i^{S*}(1-\pi_j^{S*})+\pi_j^{S*}][V(2)-1]-c(\pi_i^{S*}).$$

First, we show that $W((S_l, S_l), V(2)^*_{RA}) < W(S_l, S_k)$. Note that

$$\begin{aligned}
W((S_l, S_k)) &= W_1((S_l, S_l); V(2)^*_{RA}, \lambda = 0) + W_2((S_l, S_l); V(2)^*_{RA}, \lambda = 0) \\
&= [\pi_1^{S*}(1 - \pi_2^{S*}) + \frac{1}{2}\pi_1^{S*}\pi_2^{S*}] + \frac{1}{2}[\pi_1^{S*}(1 - \pi_2^{S*}) + \pi_2^{S*}][V(2)^*_{RA} - 1] - c(\pi_1^{S*}) \\
&+ [\pi_2^{S*}(1 - \pi_1^{S*}) + \frac{1}{2}\pi_2^{S*}\pi_1^{S*}] + \frac{1}{2}[\pi_2^{S*}(1 - \pi_1^{S*}) + \pi_1^{S*}][V(2)^*_{RA} - 1] - c(\pi_2^{S*}) \\
&> [\pi^{S**}(1 - \pi^{S**}) + \frac{1}{2}(\pi^{S**})^2] + \frac{1}{2}[\pi^{S**}(1 - \pi^{S**}) + \pi^{S**}][V(2)^*_{RA} - 1] - c(\pi^{S**}) \\
&+ [\pi^{S**}(1 - \pi^{S**}) + \frac{1}{2}(\pi^{S**})^2] + \frac{1}{2}[\pi^{S**}(1 - \pi^{S**}) + \pi^{S**}][V(2)^*_{RA} - 1] - c(\pi^{S**}) \\
&= \pi^{S**}(2 - \pi^{S**})V(2)^*_{RA} - 2c(\pi^{S**}) \\
&= W((S_l, S_l), V(2)^*_{RA}).
\end{aligned}$$

The first inequality in the fourth line follows from the fact that π^{S*}_{RA} maximizes the firms' expected payoffs within the research alliance and $\pi^{S*}_{RA} \neq \pi^{S**}$ according to Claim 3.

Now recall that $W((S_l, S_k)) = W((S_l, S_l); V(2)^{**})$ by the definition of $V(2)^{**}$. Then, since $W((S_l, S_k)) > W((S_l, S_l), V(2)^*_{RA})$, it follows that

$$W((S_l, S_l), V(2)^{**}) > W((S_l, S_l), V(2)^*_{RA}).$$

Then, the monotonicity of $W((S_l, S_l), V(2))$ in $V(2)$ shows that $V(2)^{**} > V(2)^*_{RA}$, which completes the proof. ■

Proof of Proposition 10

Proof. The firms choose the same site for all $V(2)$ with $V(2) \geq V(2)^*_{RA}$ according to Proposition 9. But, according to Lemma 4, $[V(2)^*_{RA}, V(2)^{**}]$ is nonempty. Then, since differentiation in site choice is efficient for all $V(2)$ with $V(2) > V(2)^{**}$ according to Proposition 4, firms' choosing the same site is inefficient. For $V(2)$ with $V(2) > V(2)^*_{RA}$, firms incentive to choose a same site coincides to that of the social planner, so firms' choosing the same site is efficient. The inefficiency result in the firms' effort choice and corresponding efficient investment choice is given in Proposition 9 and Corollary 1. ■

Proof of Corollary 2

Proof. Recall that the firm i's expected payoff from choosing the same site, S_l in the equal sharing R&D game is

$$\begin{aligned} W_i((S_l, S_l); V(2)^*_{ES}) &= \{\pi_i^{S*}(1-\pi_j^{S*}) + \frac{1}{2}\pi_i^{S*}\pi_j^{S*}\}V(2)^*_{ES} - c(\pi_i^{S*}) \\ &= \frac{1}{2}\pi_{ES}^{S*}(2-\pi_{ES}^{S*})V(2)^*_{ES} - c(\pi_{ES}^{S*}) \end{aligned}$$

where the equilibrium effort level conditional on choosing the same site in the equal sharing R&D game is denoted by π_{ES}^{S*}. Now recall that the firm i's expected payoff choosing the same site S_l within the research alliance is $W_i((S_l, S_l); V(2)^*_{RA}, \lambda = 0)$

$$\begin{aligned} &= [\pi_i^{S*}(1-\pi_j^{S*}) + \frac{1}{2}\pi_i^{S*}\pi_j^{S*}] + \frac{1}{2}[\pi_i^{S*}(1-\pi_j^{S*}) + \pi_j^{S*}][V(2)^*_{RA} - 1] - c(\pi_i^{S*}) \\ &= \frac{1}{2}\pi_{RA}^{S*}(2-\pi_{RA}^{S*})V(2)^*_{RA} - c(\pi_{RA}^{S*}) \end{aligned}$$

where the equilibrium effort level conditional on choosing the same site in the research alliance is denoted by π_{RA}^{S*}, given that both firms' equilibrium effort level is same in the equilibrium with $\lambda = 0$. Now recall that

$$W_i((S_l, S_l); V(2)^*_{ES}) = W_i((S_l, S_l); V(2)^*_{RA}, \lambda = 0) = W_i((S_l, S_k)).$$

Hence, we have $\pi_{RA}^{S*} = \pi_{ES}^{S*}$ if and only if $V(2)^*_{RA} = V(2)^*_{ES}$. But, note that the marginal revenue from increase in π^{S*} in the research alliance is smaller than that conditional on choosing the same site in the equal sharing R&D game for given $V(2)$ with $V(2) > 1$. Hence, the case that $\pi_{RA}^{S*} = \pi_{ES}^{S*}$ should be excluded where there exists compatibility externality.

Now recall that for given $V(2)$, the firms' marginal revenue from increase in π^{S*} conditional on choosing the same site in the equal sharing R&D game is greater than the social marginal revenue, which results in $\pi_{ES}^{S*} > \pi^{S**}$ and $V(2)_{ES}^{S*} < V(2)^{**}$ as proven in Proposition 5 and Lemma 2 respectively. Therefore, since the firms' marginal revenue from increase in π^{S*} conditional on choosing the same site in the equal sharing R&D game is greater than that in the research alliance for given $V(2)$, it follows that $\pi_{RA}^{S*} > \pi_{ES}^{S*}$ and $V(2)_{ES}^{S*} < V(2)_{RA}^{S*}$, which completes the proof. ■

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