Collective Innovation in a Standard Setting Context

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Abstract

We develop a model of collective innovation for the repeated updating of a technology standard. We characterize equilibria in an open or consortium standard and proprietary standard environments. We highlight a possible free riding problem due to the public goods nature of the open standard. This implies a larger number of firms in a standard may have an adverse effect on investment. However this effect may be balanced and even offset by positive network effects of larger participation. Turning as a second step to a proprietary standard, we show that introducing greater reward to a firm among the SOS members that provides the critical improvement also can overcome the free riding problem. We derive the rule for setting optimal rewards.

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1 Introduction

The object of this paper is to understand how ownership will effect investment in improvement of the standard when there are many technologies in the standard. When multiple technologies are required to implement a standard, organizing a patent pools is known to be welfare improving, once a standard has been established (Lerner and Tirole (2004)). In this paper we analyze how the ownership arrangement of a standard dictates investment in the future standard.

While Windows is an example of a proprietary standard with one owner that has been updated many times, there are several examples of standards evolving when the improvement is undertaken by SSO members or member of a patent pools. MPEG is an example of a standard that has evolved. MPEG-1, the standard for moving pictures and audio files on storage devices was established by the Motion Pictures Expert Group, a working group of ISO/IEC, an SSO. The standard was approved by the ISO/IEC in 1994. The same group established the MPEG-2, coding standard of audio and vidual files files used in Digital Television and DVDs which was approved in 1997, a patent pool to license the patents, MPEG LA , was established in 1996 with 9 firms and one university. The standard pool has over 700 members (patent owners) now. The same group has since developed the MPEG-4, for multimedia applications in 1998 (version 2 in 1999). This standard has two parts, visual and audio, and they are licensed separately by MPEG LA and Via Licensing.[1] As shown in Table 1, there are many firms that have been active through the development of the standard.

The next generation of DVDs, Blu-ray, is a development of the DVD visual standard. The DVD audio and visual standard is licensed by two patent pools and Thompson Electric. (Table 2). In terms of technology evolution, it is a new generation of the DVD standard. One can see from the major patent holders that Blu-ray was development by members of 3C while 6C developed the once rival HD DVD standard (Tables 3 and 4). We also note that there are some notable new entrants, as was the case with MPEG-2.

Although there are multiple firms in our framework, it should be noted that they all have a stake in a single standard. In case of DVDs, having a single standard is essential because contents must be produced. It is difficult or impossible to produce DVDs that run on multiple standards. This differs from the standard wars nature of the analysis by Cabral and Salant (2008). As the authors explain, benefit from standardization is from economies of scale in production, such as in mobile telephone standards. People with phones with different standards are able to communicate. There is no similar interoperability that is economically viable for DVDs.

We are interested in firms that innovate to improve the common standard, not to win standard "wars". Considering first an open or consortium standard where all contributors are remunerated equally, we highlight a possible free riding problem due to the public goods nature of the standard. This implies a

[1] MPEG-7, a standard for multimedia search and filtering was established in 2001. A call for owners of MPEG-7 essential patents was made by a patent licensing company Via Licensing in 2003. MPEG-21 is under development by MPEG-21.

larger number of firms in a standard may have an adverse effect on investment. However this effect may be balanced and even offset by positive network effects of larger participation. Turning as a second step to a proprietary standard, we show that introducing greater reward to a firm among the SOS members that provides the critical improvement also can overcome the free riding problem. We derive the rule for setting optimal rewards.

Our focus is the same as recent literature on allocation of returns from investment in complementary technologies (Gilbert and Katz (2007)) and patent pools. While previous studies of patent pool allocation has concentrated on efficient use of patents or patent pools stability (Lerner, Strojwas and Tirole (2007), Leveque and Ménière (2007), Aoki and Nagaoka (2004)), we focus on allocation to induce investment in the technology that constitute the patent pool. Thus our work is is complementary to Aoki and Schiff (2008) which also studies effect of patent pool allocation on upstream innovation but there is no network effect.

2 The model

2.1 Value of the standard

We consider a model in which k symmetric firms use a technology standard and invest in R&D to develop the next generation of this standard. Let $T \in N$ denote the generation of the standard. Generation T of the standard is replaced by generation $T+1$ once one of the firms - denoted as the technology leader - has succeded in developing an improved version. The renewal of the standard depends on the firms' R&D investments. By investing $x_i c$ up front, firm i can develop a new generation of the standard in delay d with a probability $1 - e^{-x_i d}$. The renewal of the standard then takes place once a firm succeeds first in developing the new generation. Hence the renewal of the standard follows a Poisson process with a hit rate $X(T) \equiv \sum_{i=1}^{k} x_i(T)$.

The instant profit flow generated by the T^{th} generation of the standard is $\Pi(T)$. Given a discount rate r, the private value $V(T)$ of generation T of the standard can be expressed as follows:

$$V(T) = \frac{\Pi(T) + X(T)V(T+1)}{r + X(T)} - cX(T) \tag{1}$$

Assume now that renewing the standard increases its private value by a factor $\theta > 1$, such that $V(T+1) = \theta V(T)$. Plugging this equation in equation (1) makes it possible to isolate $V(T)$ and express it as a function of $X(T)$:

$$V(T) = \frac{\Pi(T) - [r + X(T)]\, X(T)\, c}{r - (\theta - 1) X(t)} \equiv \widehat{V}(X(T)) \tag{2}$$

Lemma 1 establishes that, under some reasonable conditions on the parameters, this expression admits a maximum in X on $\left[0, \frac{r}{\theta-1}\right[$.

Lemma 1 *$\widehat{V}(X)$ admits a maximum $\widehat{X}$ on $\left[0, \frac{r}{\theta-1}\right[$ if $0 < \widehat{V}'(0) < \frac{c}{\theta-1}$, with $\widehat{V}'(0) = \frac{(\theta-1)\Pi}{r^2} - c$. This maximum value is given by:*

$$\widehat{X} = \frac{r}{\theta-1}\left[1 - \sqrt{\theta - \frac{\Pi(\theta-1)^2}{cr^2}}\right]$$

Proof. See Appendix. ■

Observe first that $\widehat{V} = \frac{\Pi(T)}{r}$ when $X(T) = 0$. Starting R&D to improve the standard is then profitable if $\widehat{V}'(0) > 0 \Leftrightarrow \frac{(\theta-1)(\Pi/r)}{r} > c$. If the cost of R&D is close to zero, investing in R&D is always profitable and $\widehat{V}$ has an explosive shape. By contrast, the condition $\widehat{V}'(0) < \frac{c}{\theta-1}$ guarantees that the R&D cost is large enough to prevent infinite levels of R&D. In that case, the value of the standard increases with $X(T)$ up to a certain threshold $\widehat{X}$, beyond which the cost of increasing R&D exceeds the marginal benefit in terms of acceleration of the standard renewal.

2.2 Equilibrium with a Single Owner Proprietary Standard

Having presented the general model of standard renewal, we consider now the extreme case of a proprietary standard, namely a standard developed entirely by a single firm. Assuming that this firm is then able to derive a profit flow Π from the standard - either through direct use or through licensing - the program of this single firm at generation T of the standard would be

$$\max_{x_i(T)} V(T) = \frac{\Pi(T) + X(T)\,V(T+1)}{r + X(T)} - cX(T)$$

Replacing $V(T+1)$ with $\theta V(T)$ and swallowing the notations in T, the corresponding FOC is:

$$(r\theta V - \Pi) = c(r+X)^2$$

which can be reexpressed as:

$$V = \frac{\Pi + c(r+X)^2}{\theta r} \equiv V^P(X) \tag{3}$$

Considering a given generation T of the standard, equations (2) and (3) characterize respectively the value of the standard for its owner as a function of total R&D, and the total R&D as a function of the value of the standard.

The equilibrium, if there is one, corresponds to the intersection(s) of these two curves in the space (X, V). If the "standard" is owned by a unique firm, it is then a pure private good, since the surplus of innovation is fully internalized by the unique firm. The equilibrium is defined by equation:

$$V^P(X) = \widehat{V}(X)$$

where $V^P(X)$ is increasing in X and convex. As stated in Proposition 2, the equilibrium is then unique, and it maximizes the value of the standard.

Proposition 2 *If there is only one firm, there is a unique equilibrium and it maximizes the value of the standard.*

Proof. See Appendix. ■

Unsurprisingly, a unique firm will invest in R&D so as to maximize the value of the standard. By contrast, difficulties and inefficiencies may arise when several firms are involved in the standard renewal process. We will consider successively two cases in the next two Sections. The first one corresponds to an entirely "open standard" environment where, in absence of premium given to the leader, the standard has the features of a pure public good. The second one corresponds to a partly proprietary standard, where the leader benefits from a specific reward.

3 Open or Consortium Standard

3.1 Collective R&D function

We consider in this Section that the standard is jointly developed by $k > 1$ firms. We assume moreover that there is no specific reward to the firm that develops a new generation of the standard. Let $\pi_i(T) = \Pi(T)/k$ and $v_i(T)$ denote respectively firm i's profit flow and discounted payoff of using generation T of the standard. Noting $x_i(T)$ the R&D investment of firm i, we can express $v_i(T)$ as follows:

$$v_i(T) = \frac{\pi(T) + \left[x_i(T) + \sum_{j \neq i} x_j(T)\right] v_i(T+1)}{r + X(T)} - x_i(T)\, c \qquad (4)$$

Consistent with our previous assumption, we assume that renewing the standard increases the payoff to each firm by a factor $\theta > 1$. We thus have $V(T+1) = \sum_i v_i(T+1) = \sum_i \theta v_i(T) = \theta V(T)$. Replacing $v_i(T+1)$ with $\theta v_i(T)$ in (4), omitting T for parsimony, the FOC is:

$$(r\theta v_i - \pi) = c\,(r + X)^2 \qquad (5)$$

Summing the FOC for all the k firms gives in turn the total R&D performed by the firms as an implict function of the observed value V of the standard:

$$\begin{aligned} \left(r\theta V - \Pi\right) &= k\left(r + X^*\right)^2 c \\ \text{where } X^* &\equiv \sum_{j=1}^{k} x_j^* \end{aligned} \tag{6}$$

Firms invest more in R&D if they observe a larger total value of the standard. Their investment is decreasing in the cost c of R&D and in the number of firms k, which denotes a free riding effect.

3.2 Equilibrium

It is useful to rewrite (6) as follows:

$$V = \frac{\Pi + kc\left(r + X\right)^2}{\theta r} \equiv V_k^F\left(X\right)$$

where $V_k^F\left(.\right)$ is increasing and convex in X on $[0, 1/r]$. The equilibrium is then defined by:

$$V_k^F\left(X\right) = \widehat{V}\left(X\right) \tag{7}$$

Note first that the existence of an equilibrium is not guaranteed anymore if $k > 1$. Given the shapes of V_k^F and $\widehat{V}\left(X\right)$, four cases are possible. Let $k^0 > 1$ be such that $V_k^F\left(0\right) = \widehat{V}\left(0\right)$; and let $\overline{k} > k^0$ be such that $V_k^F\left(X\right)$ and $\widehat{V}\left(X\right)$ have a point of tengency. Then:

Proposition 3 *Equilibria in a free standard environment. There exist $k^0 > 1$ and $\overline{k} > k^0$ such that:*

- If $1 < k < k^0$, there is a unique, stable equilibrium
- If $k^0 \leq k < \overline{k}$, there are two equilibria (the curbs cut twice), one of which only is stable (the one with the larger R&D spending)
- If $k = \overline{k}$, there is a unique equilibrium (which is unstable on the left hand side)
- If $\overline{k} < k$, there is no equilibrium

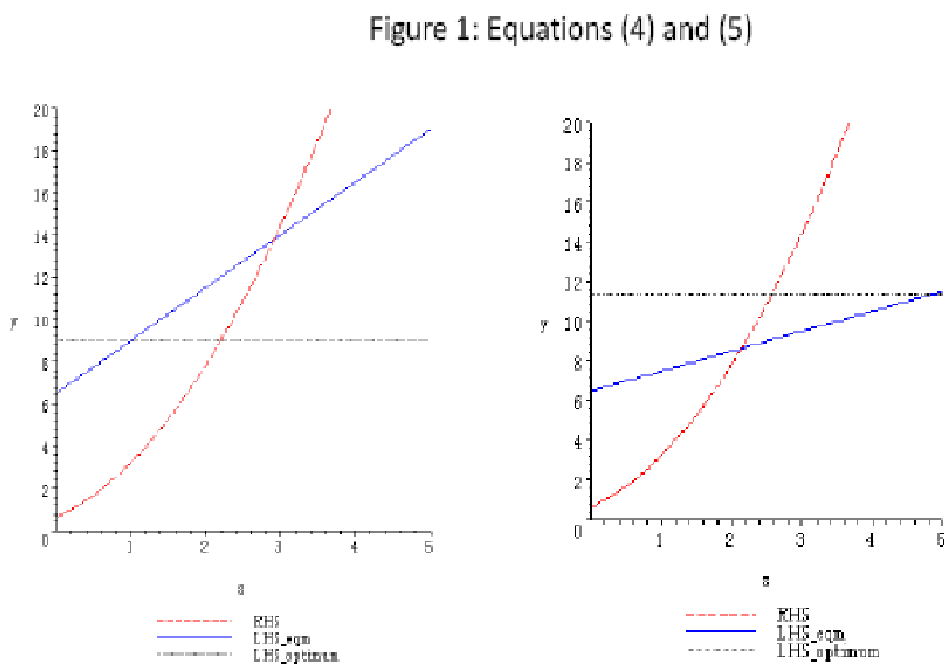

Figure 1: R&D equilibria in a free standard with $k \geq 2$

Figure 1 illustrates these results. Holding Π constant, it is obvious that $\frac{\partial V_k^F(X)}{\partial k} > 0$. Hence, the larger the number of firms involved in the standard, the lower the total amount of R&D. This is a direct and normal implication of the public good nature of the standard.

Proposition 4 *Holding constant the total profit flow generated by the standard, the total amount of R&D is decreasing in k and thus suboptimal for $k > 1$.*

3.3 New entrants

Our last statement on the public good nature of the standard may however be exagerated. Indeed standards are created to capture network effects and it is likely that their value increases with the number of users. A firm i that decides to use a standard may for instance increase the total profit flow Π. To capture this possibility, we assume now that the total profit flow Π generated by the standard is increasing in the number of firms: $\partial \Pi / \partial k > 0$.

What is then the effect on total R&D of the entry of a new firm? Applying the envelop theorem to equation (7), we can express dX^* / dk as follows:

$$\frac{dX^*}{dk} = \left[\frac{\partial\left(\widehat{V} - V_k^F\right)}{\partial X}\right]^{-1}\left[\frac{\partial V_k^F}{\partial k} - \frac{\partial\left(\widehat{V} - V_k^F\right)}{\partial \Pi}\frac{\partial \Pi}{\partial k}\right] \tag{8}$$

Clearly, the first term in bracket on the right hand side is negative. Moreover we have always $\frac{\partial V_k^F}{\partial k} > 0$. It follows unsurprisingly that $\frac{dX^*}{dk} < 0$ if $\frac{\partial \Pi}{\partial k} = 0$, since a new firm then only accentuates the free riding problem pertaining to the public good nature of the standard. Assuming that $\frac{\partial \Pi}{\partial k} > 0$ however introduces some ambiguity. Indeed it can be checked easily that $\partial\left(\widehat{V} - V_k^F\right)/\partial\Pi > 0$. The second term in the last bracket of equation (8) thus captures the R&D increase induced by the new entrants specific profit flow. Developing the expression in the last brackets and rearranging show that total R&D may then increase with the number of firms if:

$$\begin{aligned} \frac{\partial \Pi}{\partial k} &> Z \\ \text{with } Z &\equiv \frac{c\,(r+X)\,[r-(\theta-1)\,X]}{\theta-1} > 0 \end{aligned}$$

and decrease otherwise. We can in turn consider the effect on the entry of new firms on the total value of the standard.

Proposition 5 *There exists $Y \in \left]0, Z\right[$ such that a new participant increases the value of the standard if $\frac{\partial \Pi}{\partial k} > Z$, and decreases it otherwise.*

Proof. By differentiating $V_k^F(X^*)$ with respect to k we obtain:

$$\frac{dV_k^F}{dk} > 0 \quad \Leftrightarrow \quad \frac{\partial \Pi}{\partial k} > -\frac{\partial \widehat{V}}{\partial X^*}\left[\frac{\partial \widehat{V}}{\partial \Pi}\right]^{-1}\frac{dX^*}{dk}$$

Note that $\frac{\partial \widehat{V}}{\partial \Pi} > 0$ and $\frac{\partial \widehat{V}}{\partial X^*} > 0$ for $X < \widehat{X}$. It follows directly that $\frac{dV^*}{dk} < 0$ if $\frac{\partial \Pi}{\partial k} = 0$ since in that case we have $\frac{dX^*}{dk} < 0$. Assume now that $\frac{\partial \Pi}{\partial k} = Z$. In that case we have $\frac{dX^*}{dk} = 0$ and thus $\frac{dV^*}{dk} > 0$. ■

This implies that the impact of new participants on the value of the standard depends on whether their participation increases the total profit flow generated by the standard once it has been adopted. The participation of a new firm has off setting effects. On the one hand it increases the total profit flow generated by the standard, and contributes additional R&D in proportion to its own profit flow. On the other hand, it accentuates the free riding problem. We have seen that the net effect on total R&D depends on the level of the profit flow of the new participant: this flow has to be large enough (e.g., $\partial\Pi/\partial k > Z$) for the R&D performed by the new firm to outweigh the free riding effect. Since the additional profit flow also increases the value of the standard, this condition is sufficient to warrant an increase in the value of the standard. By contrast, the participation of a firm may decrease the value of the standard if it generates too low a profit flow (e.g., $\partial\Pi/\partial k < Y$ with $Y < Z$), such that the marginal contribution in terms of R&D and profit does not off set the free riding effect.

4 Proprietary Standard

The firms' R&D strategies depend to a large extent on whether the technology leader is given a specific reward. Let now $v_L(T)$ and $v_F(T)$ denote the value of generation T of the standard respectively for the leader and for a follower, with $v_L(T) \geq v_F(T)$ and $V(T) = v_L(T) + (k-1)\,v_F(T)$. For a given firm $i \in \{L, F\}$, these values can be expressed as follows:

$$v_i(T) = \frac{\pi_i(T) + x_i(T)\,v_L(T+1) + \sum_{j\neq i} x_j(T)\,v_F(T+1)}{r + X(T)} - x_i(T)\,c$$

Following our initial assumption, renewing the standard increases the values of the leader and followers by a factor $\theta > 1$. We thus have $V(T+1) = v_L(T+1) + (k-1)\,v_F(T+1) = \theta v_L(T) + (k-1)\,\theta v_F(T) = \theta V(T)$. Using these notations and swallowing notations in T, the FOC of firm i writes:

$$(r\theta v_L - \pi_i) + \theta\,(v_L - v_F)\sum_{j\neq i} x_j = c\,(r+X)^2 \tag{9}$$

There are two types of incentives to invest in the standard renewal. The first one is the intrinsic benefit of replacing the old technology with a better one $(rv_L - \pi_i)$. The second one corresponds to the strategic incentive not to be relegated as a follower if another firm innovates first: $\theta\,(v_L - v_F)\sum_{j\neq i} x_j$. Note that the latter incentive is increasing in the R&D effort of the other firms.

It is useful to use a specific notation to capture the leader's advantage. Let $\Delta \in \left[\frac{1}{k}, 1\right]$ denote the leader's premium such that

$$\begin{cases} v_L = \Delta V \\ v_F = \frac{(1-\Delta)V}{k-1} \end{cases}$$

In other words, Δ represents the share of the total value of the standard that is appropriated by the leader. In absence of premium given to the leader ($\Delta = 1/k$), observe that the open standard becomes a particular case of the free standard we analyzed in the previous Section.

Summing all individual FOC (9) and introducing Δ yields the following collective R&D function:

$$\begin{aligned}(r\theta k v_L - \Pi) + (k-1)\,\theta\,(v_L - v_F)\,X^* &= k\,(r+X^*)^2\,c \\ &\Leftrightarrow \\ (r\theta k\Delta V - \Pi) + (k\Delta - 1)\,\theta V X^* &= k\,(r+X^*)^2\,c. \end{aligned} \tag{10}$$

The presence of k in the term on the right hand side corresponds to the free riding effect observed in the open standard. While k does not appear in the term on the left hand side when $\Delta = 1/k$, it is now present twice for any constant $\Delta > 1/k$, each time with a positive impact on total R&D. In the first term on the left hand side, the direct incentive to innovate is now driven by $kv_L = k\Delta V > V$ for $\Delta > 1/k$. In other words, the premium generates a form of patent race, thereby boosting R&D efforts. Moreover the second term on the left hand side is positive only for $\Delta > 1/k$ and corresponds to the firms' strategic incentive to innovate in order not to be relegated as a follower in the next generation of the standard. Holding Δ constant, we can observe easily that it is also increasing in k. As stated in Proposition 5, these two effects overweigh the free riding effect for any $\Delta > 1/k$.

Proposition 6 *The collective R&D effort X^* is*

- *increasing in the observed value V of the standard*
- *increasing in $\Delta \in (1/k, 1]$*
- *increasing in k*

Proof. See Appendix ■

The total R&D performed by the firms is larger the higher the observed value V of the standard, as expected. It is moreover increasing in the level of the premium Δ given to the technology leader. Interestingly, it is now also increasing in the number of firms k for any constant $\Delta \in (1/k, 1]$. This latter result is in sharp contract with the free riding problem observed in the open standard.

4.1 Equilibrium

By rearranging (10) we can express the collective R&D function as follows:

$$V = \frac{\Pi + kc\,(r+X)^2}{\theta\,[k\Delta\,(r+X) - X]} \equiv V^F_{k,\Delta}(X) \tag{11}$$

where $V^F_{k,\Delta}(.)$ is increasing and convex in $X \in [0, r/(\theta-1)]$. The equilibria, if any, are defined by the following equation:

$$V^F_{k,\Delta}(X) = \widehat{V}(X)$$

Proposition 7 *Equilibria in an open standard environment ($k \geq 2$).*

There is a unique, stable equilibrium if $\Delta > \overline{\Delta}$, where $\overline{\Delta} = 1/2\theta + cr^2/\theta\Pi$.

If $\Delta < \overline{\Delta}$:

- *There is a unique, stable equilibrium if $k \geq k_\Delta^0$*
- *There are two equilibria, one of which only is stable (the one with the larger R&D spending) if $\overline{k_\Delta} < k < k_\Delta^0$*
- *There is a unique equilibrium (which is unstable on the left hand side) if $k = \overline{k_\Delta}$*
- *There is no equilibrium if $k < \overline{k_\Delta}$*

where $\overline{k_\Delta}$ is such that $V_{k,\Delta}^F(X)$ and $\widehat{V}(X)$ have a tangency point in $[0, r/(\theta-1)]$, and

$$k_\Delta^0 = \frac{\Pi/r^2}{\Delta\theta\Pi/r^2 - c}$$

Proof. Given the shapes of $V_{k,\Delta}^F(X)$ and $\widehat{V}(X)$, we have a unique equilibrium if $V_{k,\Delta}^F(0) \leq \widehat{V}(0)$ which is equivalent to:

$$k \geq \frac{\Pi/r^2}{\Delta\theta\Pi/r^2 - c} \equiv k_\Delta^0$$

It follows from $\widehat{V}'(0) > 0$ that $\frac{\Pi/r^2}{\theta\Pi/r^2 - c} < 1$. Hence this condition is always true for $\Delta = 1$. The threshold k_Δ^0 is however decreasing in Δ. We have $k_\Delta^0 > 2$ for

$$\Delta < \frac{1}{2\theta} + \frac{c}{\theta\Pi/r^2} \equiv \overline{\Delta}$$

■

The equilibria are thus similar to those found in the case of the free standard, except for the important difference that the order of the thresholds is now reversed as k increases. The larger the number of firms, the more likely it is to have a unique, stable equilibrium.

4.2 Optimal premium

It is interesting to see how the premium Δ affects the efficiency of the R&D effort, and whether it can be used to maximize the value of the standard. We know that the optimal R&D effort corresponds to the reaction function of a single firm, which – using (3) – can be expressed as:

$$r\theta\widehat{V} - \Pi = \left(r + \widehat{X}\right)^2 c$$

Using in turn (11), the collective reaction function with $k > 1$ and $\Delta \geq 1/k$ can be expressed as:

$$\theta \Delta V (r+X) - \frac{(\Pi + \theta V X)}{k} = (r+X)^2 c$$

Equating the left hand sides yields the following equation:

$$k\theta\Delta\widehat{V}\left(r+\widehat{X}\right) = k\left(r\theta\widehat{V} - \Pi\right) + \left(\Pi + \theta\widehat{V}\widehat{X}\right)$$

Solving now for Δ and rearranging gives:

$$\Delta^*(k) = 1 - \frac{k-1}{k}\frac{\widehat{V} + c\widehat{X}}{\theta\widehat{V}} \tag{12}$$

It can be checked easily that $\Delta^*(k) \in (1/k, 1]$. Since X^* increases in Δ and $\Delta = 1/k$ yields suboptimal investment, it indeed follows that $\Delta^*(k) > 1/k$ for $k \geq 2$.

Proposition 8 *For any $k \geq 2$, the optimal R&D investment can be obtained at equilibrium by setting a premium $\Delta^*(k) = 1 - (k-1)\left(\widehat{V} + c\right) / \left(k\theta\widehat{V}\right)$. R&D investment at equilibrium is insufficient for $\Delta < \Delta^*(k)$, and excessive for $\Delta > \Delta^*(k)$.*

Interestingly, the optimal premium Δ^* is decreasing in the number k of firms. This is due to the strategic incentive to innovate that increases with k for any $\Delta > 1/k$.

It is also interesting to check whether the premium given to the leader is acceptable to the other firms. In particular, the previous leader may be reluctant to become a follower if the premium is defined ex post, e.g. after the innovation has been developed. A previous leader will accept to become a follower if:

$$\frac{(1-\Delta)}{k-1}\theta\widehat{V} \geq \Delta\widehat{V} \quad \Leftrightarrow \quad \Delta \leq \frac{\theta}{k+\theta-1} \equiv \overline{\Delta}(k) \tag{13}$$

The lower the innovation value θ, and the higher the number firms k, the lower the cap put on the ex post premium. Some simple calculations show that the premium Δ^* satisfies condition (13) if:

$$k \leq 1 + \frac{\theta c\widehat{X}}{(\theta-1)\widehat{V} - c\widehat{X}} \equiv k^{\Delta}$$

Proposition 9 *Reaching the optimal R&D effort through ex post negotiation is possible only if $k \leq k^{\Delta}$.*

5 Conclusion

Considering the problem of collective R&D investment for the renewal of a cooperative technology standard, this paper highlights several interesting results about the efficiency of open and proprietary standards.

We first obtain a general result of sub-optimal R&D investment in open standards. This is due to the public goods nature of such standards where all contributors make equal gains. However, having several firms participating in the standard renewal may nevertheless increase the value of the standard, and the total R&D effort, if their presence generates substancial network effects.

We consider alternatively the case of a proprietary standard, where firms that provide a critical improvement are given greater reward. We show that introducing this asymmetry in rewards reverses the effect of a large participation on total R&D, and may thus result in over-investments. We derive the rewarding rule that yields efficient R&D investment. We show that this rule implies a substantially higher reward for the technology leader, and may not be acceptable ex post by the other contributors if they are numerous. This result thus upholds policy arguments in favor of ex ante setting of reasonable royalty in standard setting organization.

6 Appendix

6.1 Proof of Lemma 1

We have $\widehat{V}(0) > 0$ since $\frac{\Pi}{r} > 0$. Moreover

$$\begin{aligned} \widehat{V}'(X) &= \frac{(\theta-1)\,\Pi - cr^2 + cX\left[(\theta-1)\,X - 2r\right]}{\left[(\theta-1)\,X - r\right]^2} \\ \widehat{V}'(0) &= \frac{(\theta-1)\,\Pi}{r^2} - c \end{aligned} \tag{14}$$

and

$$\widehat{V}''(X) = 2\frac{\Pi\,(\theta-1)^2 - cr^2\theta}{\left[r - (\theta-1)\,X\right]^3}$$

Assuming that $r > (\theta-1)\,X$, we can then show easily that

$$\widehat{V}''(X) > 0 \qquad \Leftrightarrow \qquad \widehat{V}'(0) > \frac{c}{\theta-1}$$

Hence:

- if $\widehat{V}'(0) > \frac{c}{\theta-1}$, then $\widehat{V}'(X) > 0$ with $V''(X) > 0$ over all the interval $\left[0, \frac{r}{\theta-1}\right[$. The shape of $\widehat{V}$ is then explosive.
- If $\widehat{V}'(0) < 0$, then $\widehat{V}'(X) < 0$ with $\widehat{V}''(X) < 0$ over all the interval $\left[0, \frac{r}{\theta-1}\right[$.As a result the R&D at equilibrium should be $\widehat{X} = 0$.

- if $0 < \widehat{V}'(0) < \frac{c}{\theta-1}$, then $\widehat{V}''(X) < 0$ and $\widehat{V}$ may admit a maximum on $\left[0, \frac{r}{\theta-1}\right[$. This unique maximum always exists because $\widehat{V}'(0) > 0$ while $\lim\limits_{X \to \frac{r}{\theta-1}} \widehat{V}'(X) = -\infty$.

The maximum is given by $V'(X) = 0$, which, given (14) and knowing that $X < \frac{r}{\theta-1}$, is equivalent to:

$$(\theta-1)\,\Pi - cr^2 + cX\left((\theta-1)\,X - 2r\right) = 0$$

This polynom admits two solutions, one of which only belongs to interval $\left[0, \frac{r}{\theta-1}\right[$:

$$\begin{aligned} X_1 &= \frac{r}{\theta-1}\left[1-\sqrt{\theta-\frac{\Pi\,(\theta-1)^2}{cr^2}}\right] > \frac{r}{\theta-1} \\ X_2 &= \frac{r}{\theta-1}\left[1-\sqrt{\theta-\frac{\Pi\,(\theta-1)^2}{cr^2}}\right] < \frac{r}{\theta-1} \end{aligned}$$

Proof of Proposition 2

Uniqueness of the equilibrium

Consider first the values of $V^P(X)$ and $\widehat{V}(X)$ when $X = 0$:

$$\begin{cases} V^P(0) = \frac{\Pi + cr^2}{\theta r} \\ \widehat{V}(0) = \frac{\Pi}{r} \end{cases}$$

We can check easily that $V^P(0) < \widehat{V}(0)$ when $\widehat{V}'(0) > 0$. Moreover we have:

$$\begin{cases} \lim\limits_{X \to \frac{r}{\theta-1}} \widehat{V}(0) = -\infty \text{ when } \widehat{V}'(0) < \frac{c}{\theta-1} \\ V^P\left(\frac{r}{\theta-1}\right) = \frac{\Pi + cr^2\left(\frac{\theta}{\theta-1}\right)^2}{\theta r} > \lim\limits_{X \to \frac{r}{\theta-1}} \widehat{V}(0) \end{cases}$$

Since $\widehat{V}(.)$ is concave and inverse-U-shaped on $\left[0, \frac{r}{\theta-1}\right[$ while $V^P(.)$ is convex and increasing on this interval, there is only one $X \in \left[0, \frac{r}{\theta-1}\right[$ such that $V^P(X) = \widehat{V}(X)$.

Optimality of the equilibrium

The optimal level of R&D can be defined by:

$$\max_X \left(\frac{\Pi + X\theta\widehat{V}(X)}{r+X} - cX\right)$$

The first order condition of this program can write:

$$\widehat{V}(X) = V^P(X) - \frac{X(r+\lambda)}{r}\widehat{V}'(X)$$

Observe that for $X = \widehat{X}$ we have $\widehat{V}\left(\widehat{X}\right) = V^P\left(\widehat{X}\right)$, while for other values of X we have $\widehat{V} \neq V^P(X)$. Hence the unique equilibrium is $X^* = \widehat{X}$.

Proof of Proposition 5

The collective R&D function can be reexpressed as follows:

$$V^*_{k,\Delta}(X) = \frac{\Pi + kc(r+X)^2}{\theta\left[k\Delta(r+X) - X\right]}$$

We can check easily that $V^*_{k,\Delta}(X)$ is positive and continuous on $\left[0, \frac{r}{\theta-1}\right]$. Indeed we have $k\Delta(r+X) - X > 0$ for any $X \geq 0$ and $1/k < \Delta \leq 1$. We demonstrate first that $V^*_{k,\Delta}(X)$ is increasing. Differentiating $V^*_{k,\Delta}(X)$ and rearranging gives:

$$\frac{\partial V^*_{k,\Delta}(X)}{\partial X} = \frac{kc(r+X)\left[(k\Delta+1)(X+r) - 2X\right] - (k\Delta-1)\Pi}{\theta\left[k\Delta(r+X) - X\right]^2} \tag{15}$$

We have then

$$\begin{aligned} \frac{\partial V^*_{k,\Delta}(X)}{\partial X} &> 0 \\ &\Leftrightarrow \\ (k\Delta-1)\left[\Pi - kc(r+X)^2\right] &< 2rkc(r+X) \end{aligned} \tag{16}$$

Clearly the $k\Delta - 1$ and the term on the right hand side are non-negative. We have moreover:

$$\Pi - kc(r+X)^2 > 0 \qquad \Leftrightarrow \qquad X < \sqrt{\frac{\Pi}{kc}} - r$$

It can be checked that $\sqrt{\frac{\Pi}{kc}} - r < 0$ when $\widehat{V}'(0) < \frac{c}{\theta-1}$. Indeed we have

$$\sqrt{\frac{\Pi}{kc}} - r < 0 \qquad \Leftrightarrow \qquad \widehat{V}'(0) < \left[(\theta-1)k - 1\right]c$$

where $\left[(\theta-1)k-1\right]c > \frac{c}{\theta-1}$ for any $\theta \geq 2$. Hence $\Pi - kc(r+X)^2 < 0$ and $\frac{\partial V^*_{k,\Delta}(X)}{\partial X} > 0$ for all $X \in \left[0, \frac{r}{\theta-1}\right]$.

We show now that $V^*_{k,\Delta}(X)$ is convex on v. Differentiating (15) gives:

$$\frac{\partial V^*_{k,\Delta}(X)}{\partial X} = \frac{2}{\theta}\frac{\Pi(k\Delta-1)^2 + ckr^2}{\left[(k\Delta-1)X + kr\Delta\right]^3} > 0$$

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