INNOVATION INCENTIVES IN TECHNICAL STANDARDS AND PATENT POOLS*

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Abstract. I study the incentives to develop complementary technologies and include them in a technical standard. I show that standardization may lead to insufficient or excessive innovation. I then study how innovation incentives and welfare are affected by two policies commonly suggested in the literature: price caps and patent pools. I find that price caps may increase or decrease innovation incentives, but that they weakly increase user surplus and welfare. I also find that an ex-ante commitment to form a patent pool weakly improves innovation and standardization incentives, and weakly increases user surplus and welfare. Therefore, both policies are desirable from a social point of view.

Keywords: Technical Standards, Innovation, Complementary Technologies, Technology Choice, Standard-Setting Organizations, Hold Up, Ex-Ante Agreements, Price Caps, Patent Pools (JEL: O31, O34, L15, L40).

1. Introduction

The prospect of opportunistic behavior (hold-up) on the part of the owners of standard-essential patents may affect the incentives to include technologies in technical standards. The extant literature studying the standard-setting process generally assumes that technologies are given when a standard is being discussed.[1] However, many technologies are developed with the objective of being included in a standard, in which case the characteristics of the standard-setting process affect the incentives to innovate.[2]

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[1]See Schmidt (2008); Simcoe (2012); Farrell and Simcoe (2012); Layne-Farrar, Llobet, and Padilla (2014); Llanes and Poblete (2014, 2018); and Lerner and Tirole (2015); for example. An exception is Llanes (forthcoming), which considers the incentives to invest to develop a single technology in a repeated-game framework.
[2]For example, when developing the 802.11n (Wi-Fi) standard, a technical group inside the Institute of Electrical and Electronics Engineers (IEEE) investigated ways to increase transmission rates, which required significant investments from Intel and other firms, and such investments were affected by the likelihood of inclusion in the standard (DeLacey, Herman, Kiron, and Lerner, 2006).

In this paper, I develop a simple model to study how the incentives to develop complementary technologies are affected by the standard-setting process.[3] Firms invest to develop technologies and then negotiate with users over their inclusion in a standard.

I begin by studying a model in which licensing fees for standard-essential patents are determined ex-post (after the standard is defined).[4] I show that the equilibrium may be inefficient for three reasons: inefficient adoption of the standard by users, inefficient development of technologies, and inefficient inclusion of technologies in the standard.

The adoption inefficiency is caused by market power, which allows patent holders to price above marginal cost. In a model with complementary components and ex-post determination of licensing fees, the pricing inefficiency is exacerbated by opportunistic behavior and the complementary-monopoly problem (Cournot, 1838).[5] Hold-up and complementary monopoly, in turn, affect patent holders' profits and user surplus, which affect the incentives to develop technologies and include them in the standard.

From a second-best welfare perspective (taking the pricing inefficiency as given), I show that the standard-setting process may lead to insufficient but also *excessive* innovation: in some cases, firms invest to develop technologies that will not be included in the standard, which is socially wasteful.

I then study two ways which have been proposed in the literature to address the problems caused by hold-up and complementary monopoly: price caps and patent pools.

[3]I focus on complementary technologies, in contrast with previous works, which have focused on substitution. Studying complementarity is important because standards are generally composed of multiple complementary technologies. For example, DVD standards' technologies are covered by more than 800 US essential patents (Joshi and Nerkar, 2011).

[4]This assumption reflects the fact that many standard-setting organizations discourage firms from negotiating licensing agreements at the standard-setting stage. For example, the VITA Standards Organization (2015) indicates that "the negotiation or discussion of license terms among working-group members or with third parties is prohibited at all VSO and working-group meetings."

[5]The complementary-monopoly problem is also known as the Cournot effect, or as royalty stacking in the innovation literature. The complementary-monopoly problem that arises in a horizontal market structure is similar to the double-marginalization problem from vertical structures. Complementary technologies may also give rise to transaction costs (Aoki and Schiff, 2010; Llanes and Poblete, 2014). The pricing inefficiency arises when firms post prices for the use of their technologies. Spulber (2016, 2017) shows that the inefficiency disappears if firms negotiate with consumers over licensing terms. I focus on settings with many patent holders and users, in which case transaction costs may render individual negotiations unfeasible.

Price caps have been proposed as a solution to prevent hold-up and improve technology choice (Swanson and Baumol, 2005; Farrell, Hayes, Shapiro, and Sullivan, 2007). When price caps are allowed, firms can commit to a maximum licensing fee that they will charge for the use of their patents if their technologies are included in the standard. In the case of substitute technologies, price caps may reduce the incentives to innovate, because they reduce innovators' profits. With complementary technologies, I show that price caps may actually have the inverse effect: because they induce firms to set lower prices, they may increase innovators' profits, and improve innovation incentives.

I show that price caps may increase or reduce innovation incentives. Interestingly though, the change in innovation incentives always causes an increase in social welfare: innovation incentives are reduced (increased) only if there would be excessive (insufficient) incentives without price caps. As a consequence, price caps weakly improve user surplus and welfare.

Patent pools have been proposed as a solution to reduce the complementary-monopoly problem (Shapiro, 2001; Lerner and Tirole, 2004; Llanes and Trento, 2012). Patent pools allow innovators to coordinate when choosing their prices, and thus weakly improve innovation incentives. Given that they increase innovation incentives, patent pools could in principle exacerbate the problem of excessive innovation and decrease social welfare. However, I show that patent pools increase innovation incentives only if there would be insufficient incentives without them. Thus, patent pools weakly improve user surplus and welfare.

This paper has two main contributions: to study how the standard-setting process affects innovation incentives, and to focus on complementary innovations, rather than substitute innovations, which has been the main focus of previous research. In Section 7, I discuss the generality and robustness of the paper's results. In Section 8, I present the main conclusions of the paper and discuss potential directions for further research.

2. The model

Two firms, $i = A, B$, may develop technologies that may be used in a standard. A continuum of users of mass one may adopt a standard based on the firms' technologies.[6]

The value of the standard for users depends on the technologies it includes. A standard which does not include any technology has value zero. A standard based on the technologies of $n \in \{1, 2\}$ firms has value $v_n \geq 0$. Two technologies are complementary if $v_2 > v_1$. However, I allow for the possibility that including a second technology in the standard decreases its value. Thus, v_2 may be smaller than v_1.

Firm i may develop technology i by incurring in a development cost of $K \geq 0$, which is sunk after development. Firms have no other fixed or variable costs.

User θ's valuation of a standard with value v is

$$v - P - \theta,$$

where $\theta \sim U[0, 1]$ represents an idiosyncratic adoption cost, and P is the sum of licensing fees paid to the owners of the standard's technologies. Users' alternative utility from not adopting the standard is normalized to zero.

Developing a standard often requires consensus between agents with stakes in the standard. The Joint Electron Devices Engineering Council (JEDEC), for instance, is formed by manufacturers and suppliers of microelectronics that participate in more than 50 technical committees and subcommittees, and determine standards through negotiation. For simplicity, I assume that users and firms decide which technologies to include in the standard following a simple voting algorithm.[7]

[6]The standard's users may represent final consumers or downstream firms that use the standard to produce goods for final consumers.

[7]The voting algorithm is inspired in the sequential bargaining games of Bloch (1996) and Ray and Vohra (1999). Larouche and Schuett (forthcoming) consider a similar bargaining procedure. The sequential voting algorithm is consistent with available evidence on the voting rules of standard-setting organizations (SSOs). Most SSOs in Chiao, Lerner, and Tirole's (2007) sample use majority voting (34%), some require a super-majority (27%), and only a small fraction require unanimity (13%). Similarly, out of 34 SSOs in Baron and Spulber's (2018) sample, 29% use a simple majority rule, 59% require a super-majority, and 12% require unanimity. I discuss alternative bargaining procedures in Section 7.

Users have a collective voting weight equal to $\alpha \in (0, 1)$, and each firm has a voting weight of $(1 - \alpha)/2$. One of the firms is selected at random to make a first offer, and that firm proposes a standard based on a subset of the invented technologies. Users and firms vote to approve the standard or not. If the standard receives a sum of positive votes greater than or equal to 0.5, then it is approved and implemented. If the standard receives a sum of votes smaller than 0.5, then it is not approved, and the other firm proposes a standard. Users and firms vote to approve the standard using the same procedure as the first proposal. If the standard proposed by the second firm is not approved, then a standard based on zero technologies is implemented.

Given that users' idiosyncratic valuation θ enters additively into utility, all users agree on which standard is best. Therefore, users vote on standards to maximize the net value of the standard $v - P$. For simplicity, I assume that if users expect the second proposal to give them the same net value as the first proposal (i.e., they are indifferent between the two proposals), they vote to approve the first proposal.

Standardization generally requires specific investments from users, which are sunk after the standard is developed (Farrell, Hayes, Shapiro, and Sullivan, 2007). These investments may include the acquisition or development of complementary goods and the costs of coordinating to adopt the same standard. Specific investments create switching costs that make it difficult for adopters to change to a different standard. Thus, I assume that the technical characteristics of a standard cannot be altered once the standard is approved.[8]

I study the following four-stage non-cooperative game. First, firms decide whether to develop their technologies. Second, users and firms vote over a standard with the voting algorithm explained above. Third, firms with technologies in the standard choose a licensing fee p_i for using their technology. Fourth, users choose whether to adopt the standard.

[8] It is straightforward to extend the model to include a cost of reverting technology choices. The main results of the paper will hold as long as this cost is sufficiently large.

The assumption that firms choose prices after the standard is defined reflects the fact that licensing fees are often negotiated ex-post. In Section 5 I study a model in which firms may commit to price caps before the standard is defined (ex-ante licensing).

3. Solution of the model

In the fourth stage, given a standard with value v and a total price P, user θ adopts the standard if $v - P - \theta \geq 0$. The total demand for the standard is

$$\Pr\left(v - P - \theta \geq 0\right) = v - P.$$

In the third stage, firms with stakes in the standard choose a price. If the standard includes the technology of one firm, this firm solves

$$\max_{p}\left(v_1 - p\right) p.$$

The optimal price is $p^* = v_1/2$, the firm's revenue is $(v_1/2)^2$, and users' net value is $v_1 - p^* = v_1/2$. If the two firms are in the standard, firm i solves

$$\max_{p_i}\left(v_2 - p_i - p_{-i}\right) p_i,$$

where $-i$ is the firm other than i. The equilibrium price is $p_A^* = p_B^* = v_2/3$, individual revenue is $(v_2/3)^2$, and users' net value is $v_2/3$.

In the second stage, if only one technology has been developed, its owner proposes a standard with $n = 1$ and users vote to accept the standard (the only alternative in this case is to select a standard with $n = 0$, which yields no value).

If two technologies have been developed, suppose the proposal by the first firm is rejected and a second firm has to propose a standard. The second firm proposes standard that solves $\max\{v_1^2/4, v_2^2/9\}$, and users vote to implement the standard offered by the second proposer (otherwise a standard with $n = 0$ is implemented and users obtain a net value of 0).

If $v_2/3 \geq v_1/2$, then the second proposer offers a standard with $n = 2$. This standard maximizes firms' revenues and user surplus, and this is accepted by all parties. The first firm proposing a standard proposes a standard with $n = 2$, which is similarly accepted. Thus, if $v_2/3 \geq v_1/2$ a standard with the technologies of the 2 firms is implemented.

If $v_2/3 < v_1/2$, then the second proposer offers a standard with $n = 1$, users vote to adopt it, and this standard is implemented. Anticipating this outcome, the first proposer offers a standard with $n = 1$, which is accepted by users and implemented. Thus, if $v_2/3 < v_1/2$ a standard with the technology of 1 firm is implemented.

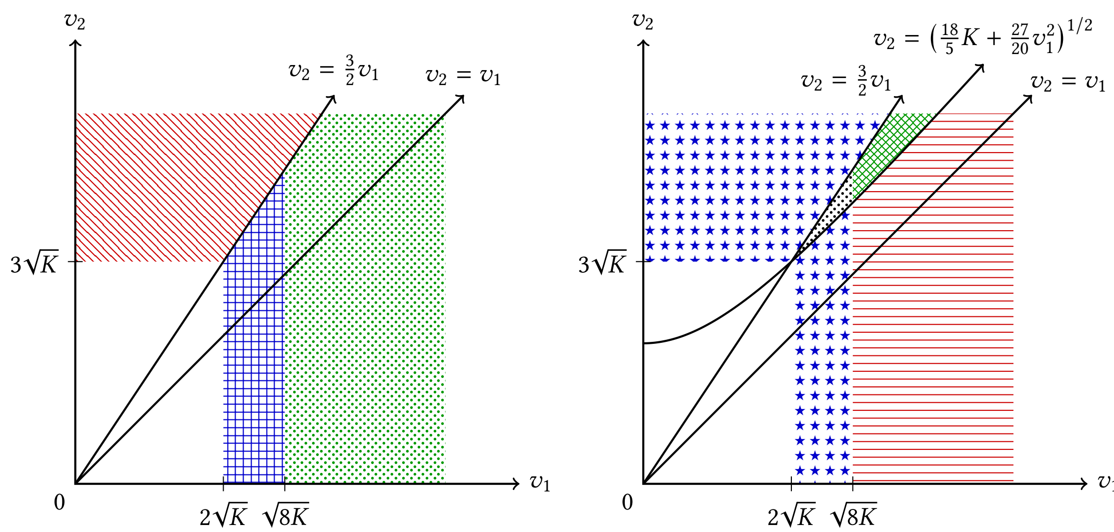
In the first stage, firms development decisions are as follows. If $v_2/3 \geq v_1/2$ and individual revenue is larger than the development cost ($v_2^2/9 \geq K$), then both technologies are developed, and a standard with $n = 2$ is implemented. If $v_2/3 \geq v_1/2$ and $v_2^2/9 < K$ then no technology is developed.

If $v_2/3 < v_1/2$ and the expected revenue when both firms develop their technologies is larger than the development cost ($v_1^2/8 \geq K$), then both technologies are developed but only one of them is included in the standard. If $v_2/3 < v_1/2$ and $v_1^2/8 < K \leq v_1^2/4$, then only one technology is developed and included in the standard. If $v_2/3 < v_1/2$ and $v_1^2/4 < K$ then no technology is developed.

Figure 1a depicts the different equilibria in the $\{v_1, v_2\}$ plane. In the dashed region (large v_2 relative to v_1 and K), both technologies are developed and included in the standard. In the dotted region (small v_2 relative to v_1, and large v_1 relative to K), both technologies are developed but only one of them is included in the standard. In the grid-filled region (small v_2 relative to v_1, and small v_1 relative to K), only one technology is developed and included in the standard.

Proposition 1 summarizes this section's results. For easiness of exposition, Proposition 1 presents summary qualitative results. Lemma A1 in Appendix A shows a full analysis with mathematical expressions for equilibrium thresholds.

Proposition 1 (Equilibrium of the base model)**.** *An equilibrium exists and is unique. There exist three regions of parameters which imply an equilibrium with innovation. If v_2 is large relative to v_1 and K, both technologies are developed and included in the standard. If v_1 is large relative to v_2 and K, both technologies are developed but only one of them is included in the standard. If v_1 is large relative to v_2 and small relative to K, only one technology is developed and included in the standard.*



(A) Equilibrium regions

(B) Welfare analysis

FIGURE 1. Equilibrium and welfare analysis of the base model

4. WELFARE

Social welfare is given by $W = S + \pi_A + \pi_B$, where S is user surplus, and π_i is firm i's profit, which is given by expected revenue minus development cost if the firm develops the technology, and zero otherwise.

Suppose that developing at least one technology is socially desirable ($K \leq \max_n v_n^2/2$). Then, the first best is to develop only those technologies which will be included in the standard, to have all users adopt the standard, and to develop both technologies only if $K \leq v_2^2/2 - v_1^2/2$.

There are three potential sources of inefficiency in the equilibrium of Proposition 1: inefficient adoption by users, inefficient technology development, and inefficient inclusion of technologies in the standard.

The inefficient adoption by users is a consequence of monopoly pricing. In this model with complementary components, the inefficiencies stemming from monopoly power are compounded by the well known complementary-monopoly problem studied by Cournot (1838). To understand the latter two inefficiencies and how they interact with pricing and adoption decisions, in what follows I study second-best welfare assuming monopolistic pricing of technologies.

If two technologies are developed and included in the standard, user surplus is $v_2^2/18$ and the sum of firms' profits is $2\left(v_2^2/9 - K\right)$. Thus, welfare is $v_2^2/18 + 2\left(v_2^2/9 - K\right)$. If one technology is developed, welfare is $v_1^2/8 + v_1^2/4 - K$. Finally, if two technologies are developed but only one is included in the standard, welfare is $v_1^2/8 + v_1^2/4 - 2K$.

It is straightforward to see that it is never optimal to develop two technologies if only one of them is going to be implemented in the standard. By standard calculations, a standard with two technologies is (second-best) socially optimal if

$$K \leq \frac{5}{18}v_2^2 - \frac{3}{8}v_1^2.$$

If $v_2 < v_1$, the right-hand side of the above inequality is negative, so it is always second-best optimal to develop one technology. If $v_2 > v_1$, the choice between one or two technologies depends on the following trade off. On one hand, having two technologies increases the value of the standard from v_1 to v_2, which can potentially increase user surplus and firms' revenues. On the other hand, having two technologies implies an additional development cost of K, and also increases the proportional welfare loss due to inefficient adoption because of the complementary-monopoly problem.

Proposition 2 follows from a comparison of the welfare properties of the equilibria in Proposition 1. For easiness of exposition, Proposition 2 presents summary qualitative results. Lemma A2 in Appendix A shows a complete second-best welfare analysis for all parameter values.

Proposition 2 (Second-best welfare)**.** *The equilibrium may have insufficient or excessive technology development from a second-best point of view. Even if innovation incentives are adequate, the equilibrium may have insufficient standardization.*

As Proposition 2 shows, the equilibrium may be inefficient because of insufficient or excessive technology development incentives. Even when innovation incentives are adequate, the equilibrium may be inefficient due to insufficient standardization.

Figure 1b shows the constrained-welfare analysis of the equilibria in Proposition 1. The equilibrium is constrained-efficient in the starred region. In the dotted area, the equilibrium is inefficient due to insufficient technology development and standardization incentives. In the grid-filled area, innovation incentives are adequate but there is insufficient standardization. In the horizontal-lines area, there is excessive technology development.

As Proposition 2 shows, welfare may be larger even with one technology even if $v_2 > v_1$. This result is due to the complementary-monopoly problem: the welfare loss from monopolistic pricing increases as the number of firms with claims on the standard increases.

In the following sections, I study whether two policies commonly proposed to address the inefficiencies of the standard-setting process (price caps and patent pools) can improve user surplus and welfare.

5. Ex-ante agreements: price caps

Ex-ante agreements–in the form of price caps–have been proposed as a way to overcome hold-up problems in standard setting (Swanson and Baumol, 2005; Farrell, Hayes, Shapiro, and Sullivan, 2007). In this section, I study the effects of price caps on innovation incentives and standardization.

As I explain in the introduction, most analyses to date have focused on the effects of price caps on adoption and on the incentives to include technologies in standards when technologies are substitutes (that is, when two technologies compete to be included in a standard). A contribution of this paper is to study their effects when technologies are complements. As I show below, when technologies are complementary, price caps may have additional effects that have not been studied before.

I study the following five-stage non-cooperative game. First, firms decide whether to develop their technologies. Second, firms that develop a technology commit to a price cap $\bar{p}_i$. Third, users and firms vote over a standard according to the voting algorithm of Section 2. Fourth, firms with technologies in the standard choose a licensing fee $p_i \leq \bar{p}_i$ for using their technology. Fourth, users choose whether to adopt the standard.

The solution of the fifth stage is as the solution of the fourth stage of the base model. In the fourth stage, firms with stakes in the standard choose a price. If $n = 1$, the firm with the technology in the standard solves

$$\max_{p \leq \bar{p}_i} (v_1 - p)\, p.$$

The optimal price is $p^* = \min\{v_1/2, \bar{p}_i\}$, revenue is ${p^*}^2$, and net value for users is $\max\{v_1/2, v_1 - \bar{p}_i\}$. If the two firms have technologies in the standard, firm i solves

$$\max_{p_i \leq \bar{p}_i} (v_2 - p_i - p_{-i})\, p_i,$$

where $-i$ is the firm other than i.

Consider now the second and third stages. Suppose $v_2/3 > v_1/2$. In the absence of a price cap, firms choose a price equal to $v_2/3$ and both are included in the standard. Thus, firms have no incentives to set a price cap lower than $v_2/3$ (committing to a lower price cap decreases revenue and does not affect standardization incentives). Thus, both firms set a price cap larger than $v_2/3$, and in the first stage the analysis is the equivalent to that of Section 3.

Suppose now that $v_2/3 < v_1/2$. In the absence of a price cap, $n = 1$ and price is equal to $v_1/2$. In the third stage, if users are offered standards with $n = 1$ by both proposers, they will accept the offer of the firm with smaller price cap. Thus, firms compete a la Bertrand to set price caps. If $v_2 \geq v_1$, firms have incentives to undercut their rival's price cap until price caps are so low that they induce an equilibrium of the third stage with $n = 2$. That is, firms choose a price cap of $\bar{p}_i = v_2 - v_1$ and in the third stage, both proposers offer a standard with $n = 2$. If $v_2 < v_1$ firms choose a price cap of $\bar{p}_i = 0$, and in the third stage proposers offer standards with $n = 1$.

In the first stage, if $v_2/3 > v_1/2$, then innovation incentives are not affected by price caps. If $v_1/2 > v_2/3$ and $v_2 > v_1$, each firm obtains a revenue of $(v_2 - 2(v_2 - v_1))\,(v_2 - v_1)$ if two technologies are developed, and $v_1^2/4$ if one technology is developed. Thus, if

$$\left(v_2 - 2(v_2 - v_1)\right)(v_2 - v_1) > K,$$

two firms develop technologies and both technologies are included in the standard, and if

$$\left(v_2 - 2(v_2 - v_1)\right)(v_2 - v_1) < K < \frac{v_1^2}{4},$$

then one technology is developed and included in the standard. If $v_1/2 > v_2/3$ and $v_2 < v_1$, firms obtain zero revenues if they both develop. Thus, if $K < v_1^2/4$, only one technology is developed and included in the standard.

If $v_2/3 > v_1/2$, user surplus and welfare are not affected by the possibility to set price caps. If $v_1/2 > v_2/3$ and two technologies are developed, user surplus is $(v_2 - 2(v_2 - v_1))^2/2$ and welfare is

$$\frac{1}{2}\left(v_2 - 2(v_2 - v_1)\right)^2 + 2\left(v_2 - 2(v_2 - v_1)\right)(v_2 - v_1) - 2K.$$

If one technology is developed, user surplus and welfare are as in Section 3. Comparing user surplus and welfare with those of the base model, I obtain the following proposition.

Proposition 3. *Price caps may increase or decrease innovation incentives, but they weakly increase user surplus and welfare.*

The proof of Proposition 3 is in Appendix B. Proposition 3 shows that price caps may increase or reduce innovation incentives. The change in innovation incentives is always *aligned* with social welfare: innovation incentives are reduced (increased) only if there would be excessive (insufficient) incentives without price caps. As a consequence, price caps weakly improve user surplus and welfare.

The result that price caps may actually enhance innovation incentives arises because technologies are complementary. Price caps induce firms to set lower prices, and thus allow them to overcome the complementary monopoly problem, which in some cases increases their profits and improves innovation incentives.

6. Price collusion: Patent pools

Patent pools have been proposed as a solution to reduce the complementary-monopoly problem (Shapiro, 2001; Lerner and Tirole, 2004). In this section, I study the effect of patent pools on innovation and standardization incentives.

I assume firms commit to joining a patent pool if both of them develop technologies and both technologies are included in the standard, in which case a patent-pool administrator sets a price for the bundle of licenses in the pool and distributes licensing proceeds equally among pool members.[9]

In the fourth stage, adoption decisions given prices are the same as in the base model. In the third stage, if only one technology is included in the standard, the optimal price is $v_1/2$, revenue is $(v_1/2)^2$, and users' net value is $v_1/2$. If both technologies are included in the standard (so the patent pool is formed), the equilibrium price for the bundle of patents is $P^* = v_2/2$, individual revenue is $v_2^2/8$, and users' net value is $v_2/2$.

[9]Given that the focus here is to study the effect of a patent pool on innovation and standardization incentives, I do not endogenize patent-pool formation. See Brenner (2009), Choi (2010), and Llanes and Poblete (2014) for analyses on the incentives to join patent pools.

In the second stage, if the proposal by the first firm proposing a standard fails, the second proposer offers $n = 2$ if $v_2 > \sqrt{2}\,v_1$, and proposes a standard with $n = 1$ if $v_2 < \sqrt{2}\,v_1$. Knowing this, the first proposer offers $n = 2$ if $v_2 > \sqrt{2}\,v_1$ and $n = 1$ if $v_2 < \sqrt{2}\,v_1$, and its proposal is accepted by users.

In the first stage, development decisions are as follows. If $v_2 \geq \sqrt{2}\,v_1$ and $v_2^2/8 \geq K$, then both technologies are developed and included in the standard. If $v_2 < \sqrt{2}\,v_1$ and $v_1^2/8 \geq K$, then both technologies are developed, but only one of them is included in the standard. If $v_2 < \sqrt{2}\,v_1$ and $v_1^2/8 < K < v_1^2/4$, then only one technology is developed and included in the standard.

Suppose $v_2 \geq (3/2)\,v_1$. If $v_2^2/9 > K$, the patent pool does not affect innovation and standardization incentives (two technologies would be developed and included in the standard even in the absence of a patent pool), but increases user surplus, firms' profits and welfare because it diminishes pricing inefficiencies. If $v_2^2/9 < K$ but $v_2^2/8 < K$, then the patent pool improves innovation incentives and thus has an even greater impact on welfare because it allows users to adopt a standard with $n > 0$.

Suppose now that $\sqrt{2}\,v_1 < v_2 < (3/2)\,v_1$. If $v_2^2/8 < K$, which implies $v_1^2/4 < K$, the patent pool does not have any impact on welfare. If $v_2^2/8 \geq K$ and $v_1^2/4 < K$, the patent pool improves innovation incentives and allows users to adopt a standard with $n > 0$ (a standard with $n = 0$ would be implemented in the absence of a patent pool). If $v_2^2/8 \geq K$ and $v_1^2/4 > K$, the patent pool improves innovation incentives and allows users to adopt a standard with $n = 2$ instead of $n = 1$. In the latter two cases, the patent pool increases user surplus and social welfare.

Finally, if $v_2 < \sqrt{2}\,v_1$, the patent pool has no effect on prices, technology development and standardization. Proposition 4 summarizes these results.

Proposition 4. *The commitment to form a patent pool weakly improves innovation and standardization incentives, and weakly increases user surplus and welfare.*

A surprising result of Proposition 4 is that pools weakly increase welfare. Patent pools allow innovators to coordinate when choosing their prices, and thus weakly improve innovation incentives. In principle, patent pools could in some cases exacerbate the problem of excessive innovation studied in Proposition 2 and Lemma A2. However, I show that patent pools increase innovation incentives only if there would be insufficient incentives without them. Thus, patent pools weakly improve user surplus and welfare, and are a socially desirable policy tool.

7. Generalizations and robustness of the results

In this section, I discuss the robustness of the results to changes in the specification of the model. Consider first the sequential bargaining procedure of Section 2. The analysis in Section 3 shows that in equilibrium firms and users always choose the technology that maximizes individual and total surplus, taking as given the number of developed technologies and pricing inefficiencies. Therefore, changing the bargaining procedure for another one in which firms and users bargain taking into account their ex-post payoffs would not affect the paper's results.

For example, Lerner and Tirole (2006) and Llanes (forthcoming) study a simple bargaining framework in which a standard-setting organization chooses a standard to maximize a linear combination of patent holders' profits and user surplus. This alternative bargaining procedure would yield the same results as the voting algorithm of Section 2.

Another alternative is to model ex-post licensing as the core of a cooperative game with non-transferable utility and the possibility of signing ex-ante licensing agreements as the core of a cooperative game with transferable utility, as in Llanes and Poblete (2014, 2018). This approach would be more flexible than studying ex-ante agreements as price caps because agents could make transfers to redistribute total surplus in any way they see fit, and constitutes an interesting direction for further research.

Consider next the assumption of a uniform distribution for users' value, which yields a linear demand function for the standard. I could alternatively have assumed a more general distribution function with non-decreasing hazard ratio, as in Lerner and Tirole (2004). This property guarantees that second-order conditions are verified and leads to monotonic comparative statics. However, the main trade-offs in the paper would still arise with this more general functional form: increasing the number of technologies in the standard improves its technical efficiency but augments the complementary monopoly problem. This trade-off is the main one at work for generating the paper's results.

I have assumed that firms and users know all relevant patents when negotiating the inclusion of technologies in the standard. Opportunism is more problematic when it is difficult to determine if relevant technologies are patented or not. In this case, patent-holders may try to hide standard-related patents until after the standard is defined. Such behavior is called *patent ambush*, and is exemplified by Rambus's alleged behavior in the development of the SDRAM memory standard. See Ganglmair and Tarantino (2014) for a detailed analysis of the incentives to disclose patents in standard-setting organizations. Studying the incentives to innovate when firms can hide relevant patents when discussing standards is also an interesting direction for further research.

8. Conclusion

I study the incentives to develop complementary technologies and include them in a technical standard. I show that standardization may give rise to three inefficiencies: inefficient adoption of the standard by users, inefficient incentives to develop technologies, and inefficient inclusion of technologies in the standard.

The most important result of the paper is to show that ex-ante negotiations of licensing terms–in the form of price caps–and patent pools mitigate such inefficiencies and weakly increase consumer surplus and welfare. Therefore, I show that both policies are desirable from a social point of view.

The papers' results can be tested using recent data on standards and pools (Baron and Spulber, 2018; Baron and Pohlmann, 2018). The paper can also be extended in a variety of ways. For example, the model can be extended to study innovation dynamics or more than two innovations or firms. The model can also be extended to understand the incentives to form a patent pool, by endogenizing patent-pool participation. These extensions present interesting directions for further research.

Appendix A: Additional results

Lemma A1 (Equilibrium thresholds in the base model)**.** *If* $v_2 \geq \max\left\{\frac{3}{2}v_1, 3\sqrt{K}\right\}$*, both technologies are developed and included in the standard. If* $v_1 \geq \max\left\{\frac{2}{3}v_2, \sqrt{8K}\right\}$*, both technologies are developed but only one of them is included in the standard. If* $\max\left\{\frac{2}{3}v_2, 2\sqrt{K}\right\} \geq v_1 < \sqrt{8K}$*, only one technology is developed and included in the standard.*

Proof. Follows from the analysis in the main text. ■

Lemma A2 (Complete second-best welfare analysis)**.** *If* $v_2 \geq \max\left\{\frac{3}{2}v_1, 3\sqrt{K}\right\}$*, both technologies are developed and included in the standard, and the equilibrium is second-best efficient. If* $\max\left\{\left(\frac{8}{3}K + \frac{20}{27}v_2^2\right)^{1/2}, 2\sqrt{K}\right\} \leq v_1 \leq \sqrt{8K}$*, only one technology is developed and included in the standard, and the equilibrium is second-best efficient. If* $\max\left\{\frac{2}{3}v_2, 2\sqrt{K}\right\} \leq v_1 \leq \max\left\{\left(\frac{8}{3}K + \frac{20}{27}v_2^2\right)^{1/2}, \sqrt{8K}\right\}$*, there is insufficient technology development and standardization in a second-best sense. If* $\max\left\{\frac{2}{3}v_2, \sqrt{8K}\right\} \leq v_1 \leq \left(\frac{8}{3}K + \frac{20}{27}v_2^2\right)^{1/2}$*, there is insufficient standardization in a second-best sense. If* $v_1 \geq \max\left\{\left(\frac{8}{3}K + \frac{20}{27}v_2^2\right)^{1/2}, \sqrt{8K}\right\}$*, there is excessive technology development in a second-best sense.*

Proof. Follows from the analysis in the main text. ■

Appendix B: Proofs not in text

Proof of Proposition 3. If $v_2/3 > v_1/2$, price caps do not have any effect on the equilibrium and welfare. Suppose $v_2/3 < v_1/2$. In the model without price caps, $n = 1$ if $v_1^2/8 > K$ and $n = 2$ if $v_1^2/4 > K > v_1^2/8$. If $v_2 < v_1$, then with price caps $n = 1$ if $v_1^2/4 > K$ and there is no equilibrium with $n = 2$. Thus, price caps weakly decrease innovation incentives, but this increases welfare. If $v_2 > v_1$, then with price caps, $n = 1$ if $(v_2 - 2(v_2 - v_1))(v_2 - v_1) > K$

and $n = 2$ if $v_1^2/4 > K > (v_2 - 2(v_2 - v_1))(v_2 - v_1)$. Note that user surplus is weakly larger with price caps, since

$$\frac{1}{2}(v_2 - 2(v_2 - v_1))^2 < \frac{1}{2}\frac{v_1^2}{4}$$

for any $v_1 > (2/3)v_2$. If

$$K < (v_2 - 2(v_2 - v_1))\,(v_2 - v_1) < v_1^2/8$$

or

$$K < v_1^2/8 < (v_2 - 2(v_2 - v_1))\,(v_2 - v_1)$$

then $n = 2$ with or without price caps, but price caps increase user surplus and welfare. If

$$(v_2 - 2(v_2 - v_1))\,(v_2 - v_1) < v_1^2/8 < K$$

or

$$v_1^2/8 < (v_2 - 2(v_2 - v_1))\,(v_2 - v_1) < K$$

then $n = 1$ with or without price caps, and price caps have no effect on user surplus and welfare. If

$$(v_2 - 2(v_2 - v_1))\,(v_2 - v_1) < K < v_1^2/8$$

then price caps decrease innovation incentives ($n = 2$ without price caps and $n = 1$ with price caps), but this increases welfare (there is no effect on user surplus). If

$$v_1^2/8 < K < (v_2 - 2(v_2 - v_1))\,(v_2 - v_1),$$

then price caps increase innovation incentives ($n = 1$ without price caps and $n = 2$ with price caps), and increase user surplus and welfare. ■

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