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STANDARD-ESSENTIAL PATENTS AND INCENTIVES FOR INNOVATION

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Standard-essential patents and incentives for innovation

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Abstract

Patent holders whose patents are essential to a standard are usually required to license their patents under fair, reasonable, and non-discriminatory (FRAND) terms. This requirement is often interpreted as a price cap such that royalties for the patents do not exceed their pre-standardisation incremental values. Using a theoretical model of innovators with interacting technologies, I consider the problem of choosing the incentive scheme to induce welfare-maximising research investments under the condition that it only uses the values created by the innovators, and analyse the prevalent interpretation of FRAND compared to the optimal scheme. It shows that in some cases, this incremental value rule does not lead to the efficient level of innovation investment.

Keywords: standardisation, standard-essential patents, FRAND, innovation incentives
JEL classification: L15, O31, O34, O38

1 Introduction

Technical standards, such as Wi-Fi or LTE for wireless communication, often involve many inventions that are protected by patents. A patented invention may be integral to the standard such that an implementer of the standard, for example a mobile phone manufacturer, must use it to produce a standard-compliant product. Such a patent becomes a *standard-essential patent* (SEP), and the manufacturer needs to obtain a licence for the

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SEP to market their products. The number of patents involved can be huge for a complex standard. For example, the LTE standard involves thousands of different patents (Baron and Pohlmann 2018).

In general, a patent holder is allowed to exclude others from using the invention. This can be detrimental to a standard, which is meant to be widely adopted. Many standard-setting organisations (SSOs) therefore require that their members commit to license their SEPs under *fair, reasonable, and non-discriminatory* (FRAND) terms.[1] One problem that FRAND licensing commitment purports to alleviate is the *patent hold-up* problem. The problem can be summarised as follows. Before a standard is codified, there may be multiple technologies that can provide similar functionalities (that is, they are substitutes), and the bargaining power of a particular patent holder at this stage is restricted by competition. However, once one particular technology is chosen as the standard, other technologies are no longer viable alternatives for standard implementers. Without restrictions on licensing, the SEP holder can capture the value of being included in the standard that is higher than its prior underlying value among competitors (Shapiro 2001; Farrell et al. 2007).

Although FRAND licensing commitment is a common feature of SSO policies, what it entails has not always been clear. Determination of 'reasonable' royalties for SEPs has been a major contention in several legal disputes. Scholars have proposed an interpretation that reasonable royalties should reflect the royalties in a hypothetical competition before the standard is set, which is the *incremental value* over the next best alternative (Swanson and Baumol 2005; Farrell et al. 2007).[2] In the United States, this incremental value interpretation has been endorsed by the Federal Trade Commission (2011) and accepted by courts in SEP-related cases.[3]

Given that patents are meant to incentivise investment in innovation, a policy that essentially caps the royalties for SEP holders is met with concerns that it excessively restricts the incentives for innovators (see e.g. Geradin and Rato 2007; Sidak 2013; Siebrasse and Cotter 2017). From the perspective of economic welfare, the pertinent question is what

[1] Lemley (2002) studies the policies of forty-three SSOs in telecommunications and computer networking industries and finds that the majority of them requires FRAND licensing.

[2] In the literature, this hypothetical competition has often been called *ex ante* competition, since it reflects the situation before the standard is decided. I do not use this terminology in the paper to avoid confusion, since such competition occurs *after* the innovation process, which is the focus of this paper.

[3] For example, the US Federal Circuit noted in *Ericsson v D-Link* (773 F.3d 1201 (2014)) that 'the patentee's royalty must be premised on the value of the patented feature, not any value added by the standard's adoption of the patented technology … to ensure that the royalty award is based on the incremental value that the patented invention adds to the product, not any value added by the standardization of that technology'.

the optimal innovation incentives should look like and whether the prevalent interpretation of reasonable royalties is optimal.

In this paper, I study the incentive to innovate when there are multiple technologies and the (incremental) value of each depends on which other technologies are available, which is usually the case in standardisation. Technologies from different innovators can be competing with each other, with the extreme case being that they are perfect substitutes, or they may complement each other such that the whole is greater than the sum of its parts. Using this framework, I consider the problem of choosing the incentive scheme to induce research investments that maximise the expected value of the technology bundle net of the research costs. The incentive scheme is restricted by a budget constraint that the revenues given to innovators come from the values that they jointly create; in other words, external subsidies are not allowed. This problem mirrors the budget-balanced multi-product pricing problem that yields the Ramsey pricing solution. Then, I define the competitive benchmark that represents the prevailing interpretation of FRAND, and evaluate the benchmark compared to the optimal incentive scheme.

The key result of this paper is that competitive royalties are not necessarily optimal, and economic welfare can sometimes be enhanced by allowing greater royalties than the competitive level. This result relates to a conventional economic wisdom that investment decisions are efficient if the marginal private incentive aligns with the marginal social contribution.[4] The competitive royalty that a patent holder can command, according to the idea of hypothetical pre-standardisation competition, is restricted by the incremental value of the technology over its best alternative. The same idea also holds true for a group of patent holders; their combined competitive royalties are restricted by their total incremental value over the best alternative standard that does not feature any of their inventions. If an innovator is rewarded exactly the incremental value of their contribution, then the marginal incentive aligns with the marginal social contribution. However, when multiple inventions are complements, the sum of individual incremental values exceeds the joint incremental value (Shapiro 2007). By imposing competitive royalties within a specific realised state of innovation, it is possible that an inventor has a competing substitute that drives down its competitive royalty (justifiably in isolation) in one realised state, but receives a competitive royalty smaller than its incremental value in another state due to complementarities, since not all inventors can simultaneously receive their individual incremental value. By allowing

[4] Pigouvian taxes (or subsidies) for externalities are one of the best-known applications of this wisdom. In the work that introduces this concept, Pigou (1920: 161) uses patent laws as an example of a tool for 'bringing marginal trade net product and marginal social net product more closely together'.

supra-competitive royalties in the former state, the marginal incentive in expectation over different states moves closer to the marginal social contribution when the incentives are considered in expectation over multiple possible outcomes.

This paper contributes to the analysis of how innovation should be incentivised in the standardisation context. The model adds a preceding stage to analyses of the standardisation process that begin after the technologies have been invented. In particular, the modelling approach for the value of technologies in a standard is similar to Lerner and Tirole (2015), and the competitive benchmark in this paper is consistent with their definition of a competitive equilibrium. The probabilistic innovation process used in this paper is also used by Layne-Farrar, Llobet, and Padilla (2014), who show that competitive royalties are not sufficient to attract innovating firms to participate in standardisation efforts when the choice of participation is endogenous. Gilbert and Katz (2011) study a similar question of dividing the value of multiple perfectly complementary technologies among inventors. Their paper uses a dynamic model in which multiple inventors compete to discover each component sequentially. In contrast to their work, my model does not feature a 'winner-takes-all' race to discover a technology, but allows each invention to potentially have complementary as well as substitute innovations.

More broadly, other papers study different aspects of innovation incentives under FRAND licensing commitments. Ganglmair, Froeb, and Werden (2012) study the enforcement of FRAND commitments and argue that damage remedies against SEP holders suboptimally restrict innovation, while Dewatripont and Legros (2013) show that FRAND licensing requirements may lead to firms claiming SEPs that are not really 'essential' to the standard.

The structure of innovation efforts in this paper can also be compared to the standard problem of incentives for teams, in which multiple agents contribute to a common goal. The model of multiple innovators contributing to the expected social welfare corresponds to the team incentive model of Holmström (1982), with the key difference being that, instead of contracting solely on the joint outcome, the principal can also contract upon individual signals (i.e. research outcomes), even though actions of individual agents remain non-contractible.

The rest of the paper is structured as follows. To set the stage, Section 2 describes a simplified example that highlights the intuition presented in this paper. Section 3 describes the model set-up for the rest of the paper, while Section 4 explains the result that the competitive benchmark is not necessarily optimal. Section 5 concludes with some caveats on how the results from this model should be interpreted.

2 A simple example

This section provides an intuitive example to the results in this paper, although the following model is not strictly a special case of the model described in Section 3.

Example 1. Suppose there is a project that has a value $v > 0$ if it is achieved. This project can be achieved in two ways: (i) it has two complementary technologies, 1 and 2, which may be invented by the corresponding firms 1 and 2, or, (ii) a free alternative, called technology 0, is found.

Technology 0 is found at no cost with an exogenous probability q. For each firm $i \in \{1, 2\}$, its attempt to invent technology i succeeds with probability x_i if it invests x_i^a/a, with $a > 2$.

The firms choose the research efforts x_1 and x_2 simultaneously. After the efforts are chosen, the outcomes of three probabilistic processes are realised. These processes are independent. Figure 1 summarises the timing within this model, including the hypothetical stages for a welfare-maximising principal and the competitive benchmark that are explained below.

Given this set-up, the expected social surplus given the research efforts x_1 and x_2 is

$$[q + (1 - q)x_1x_2]v - \frac{x_1^a}{a} - \frac{x_2^a}{a}. \tag{1}$$

Assume that the values of q and v are such that the research efforts that maximise the expected surplus are interior in $[0, 1]^2$. From the first-order conditions, the (unconstrained) surplus-maximising research efforts are

$$x_1 = x_2 = [(1 - q)v]^{1/(a-2)}.$$

Now, consider a principal who cannot directly choose or contract on the research efforts, but can design a revenue scheme for firms based on the realised outcomes. The rule is announced before the firms make their decisions. For simplicity, suppose that the principal must choose a scheme of the following form: each firm i receives $\overline{\rho}$ if technologies 1 and 2 are invented while technology 0 is not, and each firm i receives $\underline{\rho}$ if technologies 0, 1, and 2, are all invented. If at least one of firms 1 and 2 does not succeed, then neither firm receives

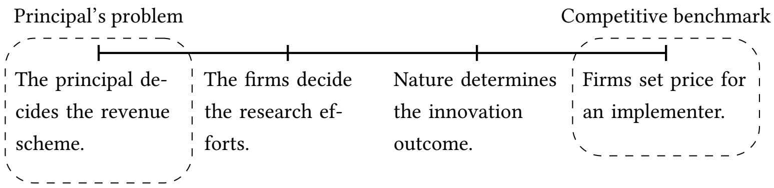

Figure 1: The timing of the model. The stages in the dashed boxes are only relevant to their respective cases.

anything.[5] Under such a scheme, firm i's expected profit is

$$[q\underline{\rho} + (1-q)\overline{\rho}]x_1 x_2 - \frac{x_i^a}{a},$$

and the non-zero symmetric Nash equilibrium of the investment game is

$$x_1 = x_2 = [q\underline{\rho} + (1-q)\overline{\rho}]^{1/(a-2)}. \tag{2}$$

The principal chooses a revenue scheme of $\underline{\rho}$ and $\overline{\rho}$ to maximise the expected surplus (1), given that the firms invest according to the equilibrium (2). In addition, the principal is restricted by the constraints that the total revenues given to the firms must not exceed the value v in any state, that is, $\underline{\rho}, \overline{\rho} \leq v/2$. If $q \geq 1/2$, then setting $\overline{\rho} = v/2$ and $\underline{\rho} = (v/2)(1-q)/q$ aligns the equilibrium research effort with the unconstrained surplus-maximising effort $[(1-q)v]^{1/(a-2)}$. On the other hand, if $q < 1/2$, then the expected surplus is maximised, given the constraints, at $\underline{\rho} = \overline{\rho} = v/2$, which induces the research effort $v/2$ that is smaller than the unconstrained optimal efforts.

The competitive benchmark is defined in the following way. Suppose the revenues that firms receive are not set a priori by a principal, but are instead determined in a Bertrand-like process after the invention outcomes are realised. Firms 1 and 2 simultaneously propose a price for their technology to an implementer, who then decides whether to pay the proposed prices for the firms' technologies. The competitive benchmark is the price in the symmetric equilibrium in which the implementer is willing to buy from the firms. (This requirement rules out coordination failures.) The symmetric equilibrium price for each of technologies 1 and 2 is $v/2$ if both of them are successfully invented and technology 0 is not found (i.e. $\overline{\rho} = v/2$). In any other outcomes, the price for technologies 1 and 2, if they exist, must be zero (including $\underline{\rho} = 0$). Recall that in the optimal scheme discussed above, firms are given

[5] The imposed structure rules out asymmetric transfers and transfers when only one firm succeeds. Allowing such transfers does not change the main intuition in this example that the optimal scheme prescribes greater transfers than the competitive benchmark.

positive revenues even when technology 0 is found ($\underline{\rho} > 0$) in contrast to the zero revenue prescribed by the competitive benchmark. This example then shows that the competitive benchmark can still be improved upon.

To understand the intuition, consider the outcome in which the firms' technologies are invented but technology 0 is not. The incremental contribution that each firm brings to the table with its technology is the full value v, since the project is worthless without it. However, with the budget constraint of v, the principal cannot give the full value to both firms, and the best thing under the constraint is to give $v/2$ to the firms if they both succeed. If technology 0 is also found, then the firms' technologies do not add any value, and in isolation it makes sense that the firms cannot command a positive revenue in this case. However, by allowing a positive revenue to firms in this outcome, the expected revenue of a firm given their incremental contribution 'offsets' what the principal cannot give in the other outcome.

In this example, the probability q that the free substitute exists is completely exogenous. The effect illustrated by this example can also be shown when all technologies are potentially invented by self-interested firms, which is the case I consider in the following sections.

3 Model

Consider the following stylised model of innovation, in which multiple technologies can be invented. Let $N = \{1, \ldots, n\}$ denote the set of risk-neutral firms; each firm $i \in N$ is endowed with one idea for a technology. Firm i's attempt to invent its technology succeeds with probability x_i if it invests $c(x_i)$, where c is an increasing and convex function with $c(0) = 0$, $c'(0) = 0$, and $\lim_{x_i \to 1} = \infty$. The research processes of all firms are simultaneous and independent. Let x be the vector of *research efforts* $(x_1, \ldots, x_n)$.

As each technology may be independently invented, there are 2^n possible states of the world. Each state is characterised by the set of available technologies. Therefore, I will also refer to the state of the world in which the set of successfully invented technologies is S as state S. The set of all possible states is the power set of N, denoted $\mathscr{P}(N)$.

If we have a set S of available technologies, then the technologies jointly create a value of $v(S)$. Assume that v is normalised such that $v(\emptyset) = 0$ and v is monotonic, that is, for any sets S and T, we have $v(S) \leq v(T)$ if $S \subseteq T$.[6] Let $\bar{v}(x)$ be the expected value of $v(S)$ given the

[6] It is conceivable that including more technologies into a standard may reduce the value of the standard, meaning that the value function of the standard is not monotonic (see Lerner and Tirole 2015). Since the standard selection process is not modelled in this paper, the monotonicity of $v(S)$ can be justified by

research efforts x, that is

$$\bar{v}(x) = \sum_{S \in \mathscr{P}(N)} \Pr(S \mid x)\, v(S),$$

where

$$\Pr(S \mid x) \;=\; \sum_{S \in \mathscr{P}(N)} \left(\prod_{j \in S} x_j \prod_{k \in N \setminus S} (1 - x_k) \right)$$

is the probability that state S is realised given the research efforts x. The expected social surplus $w(x)$ can then be written as

$$w(x) = \bar{v}(x) - \sum_{i \in N} c(x_i).$$

As the 'first-best' benchmark, let x^* be the research efforts that maximise $w(x)$. For the rest of this paper, I assume that x^* is the unique local and global maximum and it is interior in $[0, 1]^n$. In most cases, it is plausible that research investment does not have an identifiable upper bound and its nature resembles more closely the interior case. With this assumption, the first-best research efforts x^* can be characterised by the first-order conditions

$$\frac{\partial \bar{v}(x^*)}{\partial x_i} = c'(x_i^*) \quad \text{for all } i \in N, \tag{3}$$

where

$$\frac{\partial \bar{v}(x)}{\partial x_i} = \sum_{S \in \mathscr{P}(N)} \Pr(S \mid x_{-i})\, [v(S) - v(S \setminus \{i\})]$$

and $\Pr(S \mid x_{-i})$ is the probability that state S is realised given that technology i exists,

$$\Pr(S \mid x_{-i}) \;=\; \sum_{S \in \mathscr{P}(N)} \left(\prod_{j \in S \setminus \{i\}} x_j \prod_{k \in N \setminus S} (1 - x_k) \right). \tag{4}$$

The difference $v(S) - v(S \setminus \{i\})$ is the incremental contribution of technology i in state S and $\partial \bar{v}(x)/\partial x_i$ is the expected incremental contribution.

Throughout this paper, the research efforts x are assumed to be non-contractible, but it is possible to specify how much each firm is paid in a particular state of the world. Let $r_i(S)$ denote the revenue that firm i receives in state S. A full schedule of revenues for all i and S is referred to as a *revenue scheme*. This revenue scheme may represent several things: it may be a commonly known pre-determined rule (for example, an established law or SSO policy on what constitutes FRAND terms), or it may be the result of backward induction

interpreting $v(S)$ as the value of the best standard that can be chosen in state S.

from a licensing game that follows.

The firms' research can then be defined as a strategic game of n players, in which each player i chooses its research effort x_i to maximise their expected profit

$$\sum_{S \in \mathscr{P}(N)} \Pr(S \mid x)\, r_i(S) - c(x_i).$$

Assume that if the game has multiple Nash equilibria, the equilibrium that produces the highest welfare $w(x)$ is chosen. With $r_i(S) \geq 0$ and the assumptions on c, the investment equilibrium $\hat{x}$ satisfies the first-order condition

$$\sum_{S \in \mathscr{P}(N)} \Pr(S \mid \hat{x}_{-i})\ [r_i(S) - r_i(S \setminus \{i\})] = c'(\hat{x}_i) \quad \text{for all } i \in N$$

with $\Pr(S \mid \hat{x}_{-i})$ defined by (4). This condition shows that any revenue schemes that feature the same value of the difference $r_i(S) - r_i(S \setminus \{i\})$ for all i and S induce identical equilibrium research efforts. For the rest of the paper, I will restrict attention to revenue schemes that only pay the firms when they succeed, that is, $r_i(S) = 0$ if $i \notin S$. If the revenue $r_i(S)$ equals the incremental value $v(S) - v(S \setminus \{i\})$, then the equilibrium efforts coincide with the first-best efforts (3).

To simplify the exposition further, let $\bar{r}_i$ denote the expected revenue that firm i receives *if its research succeeds*, that is, for given research efforts x,

$$\bar{r}_i = \sum_{S \in \mathscr{P}(N)} \Pr(S \mid x_{-i})\, r_i(S), \tag{5}$$

and let $\bar{r}$ denote the vector $(\bar{r}_1, \dots, \bar{r}_n)$.[7] Firm i's expected profit can then be written as $x_i \bar{r}_i - c(x_i)$ and the Nash equilibrium of the investment game can be defined as research efforts $\hat{x}$ that satisfy

$$\bar{r}_i = c'(\hat{x}_i) \quad \text{for all } i \in N. \tag{6}$$

The effort $\hat{x}_i$ that satisfies (6) is unique for each $\bar{r}_i$ and increasing in $\bar{r}_i$.

Consider a hypothetical principal who sets a revenue scheme to maximise the expected social surplus $w(x)$, given that firms invest according to the investment equilibrium. In Section 4.1, I consider a simpler problem in which the principal chooses an expected revenue vector $\bar{r}$ such that, with the equilibrium efforts $\hat{x}$ defined by (6), the total expected revenues

[7] This formulation of $\bar{r}_i$ that sums over $S \in \mathscr{P}(N)$ is possible given that $r_i(S) = 0$ for $i \notin S$.

given to all firms do not exceed the expected value:

$$\sum_{i \in N} \hat{x}_i \bar{r}_i \leq \bar{v}(\hat{x}). \tag{7}$$

This is a standard contracting problem with one budget constraint.[8] The outcome of this constrained optimisation problem serves as the upper boundary of the second-best benchmark. After that, I will define a competitive benchmark within this framework, and evaluate its performance in comparison to the second-best outcome.

The constraint (7) is formulated in expected terms and does not restrict the revenues given to innovators in a particular state. In Section 4.3, I consider the problem in which the total revenues given to the firms must not exceed the value in each state, that is,

$$\sum_{i \in S} r_i(S) \leq v(S) \quad \text{for all } S \in \mathscr{P}(N). \tag{8}$$

The competitive benchmark is again compared to the second-best outcome of this constrained optimisation problem.

4 Analysis

4.1 Optimal revenue scheme under the constraint in expected terms

Consider the problem of choosing the vector of expected revenues $\bar{r}$ to maximise the expected social surplus $w(x)$, given the equilibrium investment effort (6) and the budget constraint (7). Proposition 1 below describes a condition for the solution of this constrained maximisation problem.

Proposition 1. *Under an aggregate budget constraint, the optimal expected revenue scheme satisfies*

$$\frac{\partial \bar{v}(x)/\partial x_i - \bar{r}_i}{\bar{r}_i} = \frac{m}{e_i} \quad \textit{for all } i \in N \tag{9}$$

with some constant $m \geq 0$ *and*

$$e_i = \frac{c'(x_i)}{x_i c''(x_i)}.$$

[8] The structure in this model is similar to that of Holmström (1982). His model can be characterised as follows: given a vector of agents' actions x, a joint value of $w(x)$ is created. A principal specifies a sharing rule $s_i(w)$ such that $\sum_{i \in N} s_i(w) \leq w$ for all w. Agent i's pay-off given the action profile x is $s_i(w(x)) - c(x_i)$. Comparing the constraints with $s_i(w(x))$ and $x_i \bar{r}_i$, $s_i(w(x))$ is not necessarily linear in x, while $x_i \bar{r}_i$ is.

Proof. For a given value of x_i, the revenue $\bar{r}_i$ is uniquely defined in the investment equilibrium condition (6). Therefore, we can consider the equivalent maximisation problem of

$$\max_{\hat{x}} w(\hat{x})$$
$$\text{subject to} \sum_{i \in N} \hat{x}_i c'(\hat{x}_i) \leq \bar{v}(\hat{x}).$$

The Kuhn–Tucker necessary conditions imply that the solution to this maximisation problem satisfies

$$\frac{\partial \bar{v}(x)}{\partial x_i} - c'(x_i) + \lambda \left(\frac{\partial \bar{v}(x)}{\partial x_i} - c'(x_i) - x_i c''(x_i) \right) = 0 \tag{10}$$

for all $i \in N$, and the complementary slackness condition

$$\lambda \left(\sum_{i \in N} x_i c'(x_i) - \bar{v}(x) \right) = 0,$$

with $\lambda \geq 0$ being the Lagrange multiplier for the budget constraint. If the first-best efforts x^* are not feasible under this budget constraint, then in the solution we have $\lambda > 0$ and $\partial \bar{v}(x)/\partial x_i - c'(x_i) > 0$. Rearranging equation (10) yields

$$\frac{\partial \bar{v}(x)/\partial x_i - c'(x_i)}{c'(x_i)} = \frac{\lambda}{1+\lambda} \cdot \frac{x_i c''(x_i)}{c'(x_i)}.$$

Letting $m = \lambda/(1+\lambda)$ and $c'(x_i) = \bar{r}_i$ we arrive at equation (9).

If the first-best efforts defined by equation (3) are feasible, then $\partial \bar{v}(x)/\partial x_i - c'(x_i) = 0$ and equation (9) holds with $m = 0$. □

The result from this maximisation problem is analogous to the Ramsey pricing formula, which in the simplest case is usually presented with a monopolist who supplies n independent goods (Baumol and Bradford 1970). In such a case, the Ramsey pricing formula for good i, determining the deviation from the first-best marginal-cost pricing, is given by $(p_i - mc_i)/p_i = \mu/\varepsilon_i$, where p_i denotes good i's price, mc_i its marginal cost, ε_i its price elasticity of demand, and μ a constant that is identical for all i. Equation (9) is the flip side of this formula with a monopsonist and n suppliers of research efforts. For all firms, the deviation of their marginal revenues $\bar{r}_i$ from their marginal contributions $\partial \bar{v}(x)/\partial x_i$ is inversely proportional to the 'elasticity' of effort, given by e_i in equation (9). The elasticity e_i measures the percentage change in firm i's effort in response to a change in the expected revenue $\bar{r}_i$.

4.2 Competitive benchmark

I will now define the competitive benchmark within this framework. Suppose that instead of a principal's decision, the firms engage in the following Bertrand-like process with an implementer after the invention stage is resolved and state S is realised. Each firm with a successful invention (that is, each $i \in S$) simultaneously proposes a price $r_i(S)$ to a representative implementer, who can choose from which firms to buy, if at all. The implementer's objective is to maximise the net value

$$v(B) - \sum_{i \in B} r_i(S)$$

where $B \in \mathscr{P}(S)$ is the implementer's chosen set of technologies.

A competitive benchmark for state S is defined as a price vector of $r_i^c(S)$ that is part of a strategy profile in this pricing game in which the implementer buys from all firms in S. This notion of competitive benchmark is consistent with the definition of Lerner and Tirole (2015).[9]

The following lemma describes a necessary condition for the competitive benchmark, especially in relation to the incremental value concept. It encapsulates the idea that, in the hypothetical pre-standardisation competition, the price that a firm can demand is the incremental value of its technology (Swanson and Baumol 2005). One point that has been less explicitly emphasised in the discussion is that the incremental value rule must be applied jointly for any group of technologies as well. This means the competitive price may be strictly less than the *individual* incremental value $v(S) - v(S \setminus \{i\})$.

Lemma 1. *In a competitive benchmark for any state S, the firms' prices $r_i^c(S)$ must satisfy, for any subset $T \in \mathscr{P}(S)$,*

$$\sum_{i \in T} r_i^c(S) \leq v(S) - v(S \setminus T). \tag{11}$$

Proof. In each state S, the consumer chooses to buy from all firms in S only if, for any subset $B \in \mathscr{P}(S)$,

$$v(S) - \sum_{i \in S} r_i^c(S) \geq v(B) - \sum_{i \in B} r_i^c(S). \tag{12}$$

[9] This condition rules out equilibria with coordination failure, in which firms with complementary technologies both choose too high prices. Alternatively, Lerner and Tirole (2015) impose that the competitive prices of technologies not bought by the implementer must be zero.

Suppose there exists a subset $T \subseteq S$ such that $\sum_{i \in T} r_i^c(S) > v(S) - v(S \setminus T)$, then

$$\left[v(S) - \sum_{i \in S} r_i^c(S) \right] - \left[v(S \setminus T) - \sum_{i \in S \setminus T} r_i^c(S) \right] = v(S) - v(S \setminus T) - \sum_{i \in T} r_i^c(S) < 0,$$

which means the buyer would prefer to buy only from firms in $S \setminus T$. Thus, inequality (12) is true only if inequality (11) is true. □

Inequality (11) defines the incremental value pricing rule, for each individual technology as well as for a group of technologies in state S. For example, if a technology i has a perfect substitute in state S, then the incremental value of i, $v(S) - v(S \setminus \{i\})$, is zero, which is its competitive price according to Lemma 1.

The competitive benchmark is not necessarily unique within this model. Given the unit demand, there are cases in which different price vectors can constitute the competitive benchmark as defined. For example, consider $v(\{1\}) = v(\{2\}) = 0$ and $v(\{1, 2\}) = v$. Then, any prices such that $r_1^c(\{1, 2\}) + r_2^c(\{1, 2\}) = v$ satisfy the definition of competitive benchmark. The results related to the competitive benchmark in this paper rely only on the necessary condition (11).

Recall that the first-best efforts are induced if each firm is paid its individual incremental value in all states. Since the competitive benchmark revenue in a certain state may be smaller than the individual incremental value, while the reverse is never possible, the competitive benchmark in such a case is not sufficient to induce the first-best efforts.

Given the following definition of complementarity, it can be shown that the competitive benchmark is not first-best if some technologies are complementary.

Definition 1. Technologies i and j are complements if, for all $S \in \mathscr{P}(N)$,

$$[v(S) - v(S \setminus \{i\})] + [v(S) - v(S \setminus \{j\})] \geq v(S) - v(S \setminus \{i, j\}) \tag{13}$$

with strict inequality (>) for some S.

Proposition 2. *If there exists a pair of technologies that are complements, then the first-best research efforts cannot be implemented by a competitive benchmark.*

Proof. The revenue scheme that induces the first-best efforts x^* must satisfy

$$\begin{aligned} x_i^* \bar{r}_i &= x_i^* \frac{\partial \bar{v}(x^*)}{\partial x_i} \quad \text{for all } i \in N \\ &= \sum_{S \in \mathscr{P}(N)} \Pr(S \mid x^*) \, [v(S) - v(S \setminus \{i\})]. \end{aligned}$$

Suppose firms i and j are complements. From the competitive benchmark condition (11) and the definition of complementarity (13), we have, for any state S,

$$\begin{aligned} r_i^c(S) + r_j^c(S) &\leq v(S) - v(S \setminus \{i, j\}) \\ &\leq [v(S) - v(S \setminus \{i\})] + [v(S) - v(S \setminus \{j\})]. \end{aligned}$$

As inequality (13) is strict for some S per definition, multiplying both sides by $\Pr(S \mid x^*)$ and sum over all S yields, with $\bar{r}_i^c$ defined analogous to (5),

$$x_i \bar{r}_i^c + x_j \bar{r}_j^c < \sum_{S \in \mathcal{P}(N)} \Pr(S \mid x^*) \ \left([v(S) - v(S \setminus \{i\})] + [v(S) - v(S \setminus \{j\})] \right).$$

Thus, the competitive benchmark does not implement the first-best efforts. □

The intuition of Proposition 2 is as follows. Since some technologies are complementary, then we cannot reward each firm the whole individual incremental value $v(S) - v(S \setminus \{i\})$. This makes it impossible for the competitive benchmark to induce the first-best efforts.

However, even if the competitive benchmark cannot attain the first best, it may still implements the second-best research efforts. The following proposition shows that this is not necessarily the case. If the competitive benchmark is not on the boundary of the feasible set, that is, there are values left on the table that we can give to firms, then increasing the revenues over the competitive benchmark can improve welfare.

Proposition 3. *If first-best efforts are not feasible and the expected revenue from a competitive benchmark is interior in the feasible region defined by the constraint* (7)*, then the benchmark does not implement the second-best research efforts.*

There exists a case in which welfare can be improved by allowing supra-competitive revenue.

Proof. From the assumption that there is a unique local and global maximum in $[0, 1]^n$, if the first-best efforts are not in the feasible set, then there is no local maximum in the interior of the feasible set. Since a maximum must exist in the compact feasible set, the maximum (or maxima) must be located on the boundary of the set.

If the competitive benchmark corresponds to an interior point, it must not induce welfare-maximising efforts in the feasible set, i.e. it does not implement the second-best research efforts.

Let $\hat{x}^c$ denote the equilibrium efforts in the competitive benchmark. From condition (11) and

$$\frac{\partial \bar{v}(\hat{x}^c)}{\partial x_i} = \sum_{S \in \mathscr{P}(N)} \Pr\left(S \,\middle|\, \hat{x}^c_{-i}\right) [v(S) - v(S \setminus \{i\})]$$

it follows that, given $\hat{x}^c_{-i}$,

$$\frac{\partial \bar{v}(\hat{x}^c)}{\partial x_i} \geq \bar{r}^c_i = c(\hat{x}^c_i).$$

Since the competitive benchmark is interior and is not a local maximum, the inequality must be strict for some $i \in N$, which means the marginal welfare is increasing in some x_i at the benchmark.

□

With Proposition 2 and Proposition 3, we see that with complementary technologies, it is possible that there is room to improve welfare without breaking the budget. This happens if in some states the full value is not paid out in the competitive benchmark. The following numerical example uses a set-up similar to Section 2, but instead of an exogenous free substitute technology, there is another pair of complementary technologies that can be chosen. The example shows that the competitive benchmark is interior in the feasible set and induces welfare that is lower than the second best.

Example 2. Suppose $n = 4$, and the value function is defined as follows:

$$v(S) = \begin{cases} 10 & \text{if } \{1,2\} \subseteq S \text{ or } \{3,4\} \subseteq S \\ 0 & \text{otherwise} \end{cases}$$

The cost function is $c(x_i) = x_i^2/(1 - x_i)$.

Under this setting, the welfare $w(x)$ is given by

$$10(x_1x_2 + x_3x_4 - x_1x_2x_3x_4) - \sum_{i \in N} \frac{x_i^2}{1 - x_i}$$

The first-best efforts that maximise $w(x)$ are $x_i^* = 0.545$ for all i. However, they are not feasible under the budget constraint (7). The effort level $x_i^* = 0.545$ requires $\bar{r}_i = c'(0.545) = 3.831$; this means $\sum x_i^* \bar{r}_i = 8.353$ exceeds the budget $\bar{v}(x^*) = 5.059$.

The second-best efforts, maximising $w(x)$ under constraint (7), are $x_i = 0.411$, which can be induced by $\bar{r}_i = c'(0.411) = 1.881$. The second-best welfare is $w(x) = 1.945$.

The symmetric competitive benchmark in this case is

$$r_1^c(S) = \begin{cases} 5 & \text{if } \{1,2\} \subseteq S \text{ and } \{3,4\} \not\subseteq S \\ 0 & \text{otherwise} \end{cases}$$

and analogously for other firms. The objective of firm 1 is to maximise the expected profit

$$\max_{x_1} \quad 5x_1x_2(1 - x_3x_4) - \frac{x_1^2}{1 - x_1}$$

and the first-order condition is

$$5x_2(1 - x_3x_4) - \frac{x_1(2 - x_1)}{(1 - x_1)^2} = 0.$$

The symmetric equilibrium given the competitive benchmark is $x_i^c = 0.384$ for all i. This equilibrium is interior, as $\bar{r}_i = c'(0.384) = 1.638$ yields $\sum x_i\bar{r}_i = 2.517$, which is smaller than $\bar{v}(x) = 2.735$. The welfare induced by the equilibrium is $w(x^c) = 1.776$.

4.3 State-contingent budget constraints

In previous sections, the problem with constraint (7) is formulated in expected terms. If we consider the revenues given to firms to be royalties from implementers, then this constraint is too lax as it allows the principal to transfer values across different states. If the principal is only allowed to distribute the available value within each state, the revenue scheme must instead satisfy the state-based budget constraints

$$\sum_{i \in S} r_i(S) \leq v(S) \quad \text{for all } S \in \mathscr{P}(N). \tag{8}$$

These constraints are stronger than the previous constraint (7); a revenue scheme that satisfies (8) also satisfies (7), but the reverse is not necessarily true.

With 2^n budget constraints (8) formulated with $r_i(S)$, the problem becomes considerably more complicated. The following results show that the result on the competitive benchmark established in the previous section still applies in this case, namely if first-best efforts are not feasible and the benchmark is interior in the feasible set defined by (8), then the benchmark does not implement the second-best efforts under these constraints. The previous analysis is based on choosing the expected revenues $\bar{r}$ to maximise the surplus $w(x)$, subject to constraint (7) on $\bar{r}$. Lemma 2 restates the constraints (8) into a set of constraints on $\bar{r}$. This means the problem of choosing a revenue scheme that satisfies (8) can still be reduced to that of choosing the expected revenues $\bar{r}$ subject to the following set of constraints (14), without specifying the (not necessarily unique) implementation of the revenue scheme.

Lemma 2. *Given the chosen research efforts x and expected revenues $\bar{r}$, there exists a revenue scheme that implements $\bar{r}$ according to* (5) *and satisfies the constraints* (8) *for all states S, if and only if $\bar{r}$ satisfies, for all states S,*

$$\sum_{i \in S} x_i \bar{r}_i \leq \sum_{T \in \mathcal{Q}(S)} \Pr(T \mid x)\, v(T), \tag{14}$$

where $\mathcal{Q}(S) = \{T \in \mathcal{P}(N) \mid S \cap T \neq \emptyset\}$ is the set of states that has at least one of the firms in set S.

Proof. First, I will show that a revenue scheme that represents $\bar{r}$ and satisfies the state-based budget constraints (8) exists only if $\bar{r}$ satisfies (14). Consider a revenue scheme that represents $\bar{r}$ and satisfies (8). Using the definition of $\bar{r}_i$ from (5),

$$\sum_{i \in S} x_i \bar{r}_i = \sum_{i \in S} \left[x_i \sum_{T \in \mathcal{P}(N)} \Pr(T \mid x_{-i})\, r_i(T) \right].$$

Note that $x_i \Pr(T \mid x_{-i}) = \Pr(T \mid x)$. Since it is imposed that $r_i(T) = 0$ if $i \notin T$, summing over all states equals summing over states that intersect with S. Thus,

$$\begin{aligned} \sum_{i \in S} x_i \bar{r}_i &= \sum_{i \in S} \sum_{T \in \mathcal{Q}(S)} \Pr(T \mid x)\, r_i(T) \\ &= \sum_{T \in \mathcal{Q}(S)} \left[\Pr(T \mid x) \sum_{i \in S} r_i(T) \right]. \end{aligned}$$

With $r_i(T) = 0$ if $i \notin T$, it must be that $\sum_{i \in S} r_i(T) \leq \sum_{i \in T} r_i(T)$. If (8) holds, it follows that

$$\sum_{i \in S} x_i \bar{r}_i \leq \sum_{T \in \mathcal{Q}(S)} \Pr(T \mid x)\, v(T).$$

Thus, we have that a scheme represents $\bar{r}$ and satisfies (8) only if $\bar{r}$ satisfies (14).

Now, I will show that the revenue scheme exists if $\bar{r}$ satisfies (14). The existence of a revenue scheme that represents $\bar{r}$ according to (5) and satisfies (8) for all states means the minimum in the following constrained minimisation problem is zero.

$$\min_{\langle r_i(S)\rangle} \quad \sum_{i\in N}\left(x_i\bar{r}_i - \sum_{S\in\mathscr{P}(N)} \Pr(S \mid x)\, r_i(S)\right)^2$$
$$\text{subject to (8) for all } S$$
$$\text{and } r_i(S) \geq 0 \text{ for all } i \text{ and } S$$

The following steps show that the constrained minimum is zero, that is a feasible revenue scheme that represents $\bar{r}$ exists, if $\bar{r}$ satisfies (14).

Consider the Kuhn–Tucker necessary conditions

$$2\Pr(S \mid x)\left(x_i\bar{r}_i - \sum_{S\in\mathscr{P}(N)} \Pr(S \mid x)\, r_i(S)\right) + \lambda_{iS} = \mu_S \qquad \text{for all } i \text{ and } S$$
$$\mu_S\left(\sum_{i\in S} r_i(S) - v(S)\right) = 0 \qquad \text{for all } S$$
$$\lambda_{iS} r_i(S) = 0 \qquad \text{for all } i \text{ and } S$$

with the Kuhn–Tucker multipliers $\mu_S \geq 0$ for each constraint (8) and $\lambda_{iS} \geq 0$ for the non-negativity constraint of each $r_i(S)$.

I will show by contradiction that if the constrained minimum is not zero then condition (14) is violated, thus the minimum is zero if $\bar{r}$ satisfies (14). Suppose the constrained minimum is strictly greater than zero and is attained at $\{r_i^0(s)\}$. There are two possibilities for each i: either $x_i\bar{r}_i < \sum_S \Pr(S \mid x)\, r_i^0(S)$ or $x_i\bar{r}_i > \sum_S \Pr(S \mid x)\, r_i^0(S)$. The case of $x_i\bar{r}_i < \sum_S \Pr(S \mid x)\, r_i^0(S)$ for any i can be ruled out since the right-hand side can always be lowered to zero.

Consider the case $x_i\bar{r}_i > \sum_S \Pr(S \mid x)\, r_i^0(S)$ for some $i \in N$. Let A be the set of every such i, that is,

$$A = \left\{ i \in N \,\middle|\, x_i\bar{r}_i > \sum_{S\in\mathscr{P}(N)} \Pr(S \mid x)\, r_i^0(S) \right\}.$$

From the necessary conditions, we have $\mu_T > 0$ for every state T such that $T \cap A \neq \emptyset$, the constraint (8) for T binds, and $r_i^0(T) = 0$ for every $i \notin A$ (since $\lambda_{iT} > 0$). Summing $\sum_S \Pr(S \mid x)\, r_j^0(S)$ over $j \in A$ then gives

$$\sum_{S\in\mathscr{P}(N)} \Pr(S \mid x) \sum_{j\in A} r_j^0(S) = \sum_{T\in\mathscr{Q}(A)} \Pr(T \mid x)\, v(T)$$

and together with $x_j \bar{r}_j > \sum_S \Pr(S \mid x)\, r_j^0(S)$ we have

$$\sum_{j \in A} x_j \bar{r}_j > \sum_{T \in \mathcal{Q}(A)} \Pr(T \mid x)\, v(T)$$

which contradicts condition (14). Therefore, if $\bar{r}$ satisfies (14), the minimum must be zero, which means there exists a feasible revenue scheme that represents $\bar{r}$. □

Condition (14) says that for an arbitrary subset S of firms, the sum of the expected revenues $\bar{r}_i$ given to them must not exceed the portion of the expected value $\bar{v}(x)$ that comes from states in which at least one firm from S is present. When the values of x and $\bar{r}$ satisfy the whole stack of such conditions, it is possible to find a revenue scheme that requires no transfers across different states, as prescribed by (8).

With constraints defined by expected revenues, the problem is now in a form similar to the problem considered in previous sections. A principal chooses expected revenues $\bar{r}$, subject to the constraints (14), to maximise the surplus $w(x)$ given the investment equilibrium (6). Proposition 3 still directly applies in this case, with the constraint (7) replaced by the set of constraints (14); the expected surplus from the competitive benchmark is not optimal, neither in the first-best nor second-best senses, if some technologies are complementary and the benchmark research efforts are interior in the feasible set defined by (14). The proof of Proposition 3 applies to a compact feasible set, it holds for the feasible set defined by these budget constraints.

While the result on the interiority survives, with more restrictive constraints the feasible set under (14) is smaller than one under (7). It remains a question whether a competitive benchmark that is interior under constraint (7) remains interior under (14). The following lemma shows that a competitive benchmark that is interior in the feasible set defined by (7) is also interior in the feasible set defined by (14).

Lemma 3. *Given x such that $x_i > 0$ for all i, if the expected revenue from a competitive benchmark is interior in the feasible region defined by the constraint* (7)*, it is also interior in the feasible region defined by the constraints* (14).

Proof. Note that $x_i > 0$ for all i means $\Pr(S \mid x) > 0$ for all $S \in \mathcal{P}(N)$.

Consider a competitive benchmark $r_i^c(S)$ that is interior in the feasible region defined by (7). The following steps show by contradiction that the expected revenues from a competitive benchmark cannot be interior in the feasible region of (7) but not interior in the feasible region of (14).

From the definition of expected revenue, the competitive benchmark being interior under constraint (7) means

$$\sum_{i\in N}\sum_{T\in\mathscr{P}(N)} \Pr(T \mid x)\, r_i^c(T) < \sum_{T\in\mathscr{P}(N)} \Pr(T \mid x)\, v(T), \tag{15}$$

while not being interior in (14) means, given that the competitive benchmark satisfies (11), the inequality (14) holds with equality for some state $S \in \mathscr{P}(N)$ such that $S \neq N$, that is

$$\sum_{i\in S}\sum_{T\in\mathscr{Q}(S)} \Pr(T \mid x)\, r_i^c(T) = \sum_{T\in\mathscr{Q}(S)} \Pr(T \mid x)\, v(T). \tag{16}$$

Given that $r_i^c(T) = 0$ if $i \notin S$, (15) and (16) implies

$$\sum_{\substack{j\in N\\ j\notin S}}\sum_{\substack{T\in\mathscr{P}(N)\\ T\notin\mathscr{Q}(S)}} \Pr(T \mid x)\, r_j^c(T) < \sum_{\substack{T\in\mathscr{P}(N)\\ T\notin\mathscr{Q}(S)}} \Pr(T \mid x)\, v(T).$$

This is true only if there exists a state $Y \in \mathscr{P}(N) \setminus \mathscr{Q}(S)$ such that

$$\sum_{i\in Y} r_i^c(Y) < v(Y),$$

which in turn can only be true if $v(Y) > 0$.

From Lemma 1, the competitive benchmark must satisfy $\sum_{i\in S} r_i^c(S) \leq v(S)$ for all S. With $r_i^c(T) = 0$ if $i \notin T$, equation (16) is true only if

$$\sum_{i\in S} r_i^c(T) = v(T) \quad \text{for all } T \in \mathscr{Q}(S). \tag{17}$$

That is, only firms in set S can receive a positive revenue in any states in the set $\mathscr{Q}(S)$ and the value in those states are fully distributed.

Now, consider any state Y' such that $Y \subseteq Y'$ and $Y' \cap S \neq \emptyset$. From Lemma 1, the competitive benchmark satisfies, given that $v(Y) > 0$,

$$\begin{aligned}\sum_{i\in Y'\setminus Y} r_i^c(Y') &\leq v(Y') - v(Y)\\ &< v(Y').\end{aligned}$$

But since $Y' \in \mathscr{Q}(S)$ by definition, this contradicts (17). Therefore, it is not possible that the expected revenue from a competitive benchmark is interior under (7), but not under (14). □

The idea of the proof is that for a constraint (14) to be binding for a set of firms S, the

Table 1: The values of each side in inequality (14) at the second-best efforts $x_i = 0.411$ from Example 3.

S	$\sum x_i \bar{r}_i$	$\sum \Pr(T \mid x)\, v(T)$
$\{1\}$	0.773	2.096
$\{1, 2\}$	1.545	2.505
$\{1, 3\}$	1.545	3.091
$\{1, 2, 3\}$	2.318	3.091
N	3.091	3.091

values in all states that contain at least one firm in S must be fully paid only to the firms in set S. However, some of the states also include firms outside of set S that have positive values by themselves. Since the revenues in the competitive benchmark is limited by (joint) incremental values, it cannot be the case that the full values in those states are rewarded to only the firms in set S.

Lemma 3 means that while the extra state-based budget constraints considered in this section potentially reduce the feasible set, they do not affect the main results on the competitive benchmark described in Proposition 2 and Proposition 3. It is possible that, with complementary technologies, the competitive benchmark does not lead to the welfare-maximising research efforts under the condition that the incentives given to the firms can only be from the values created by the available technologies in a particular state.

The following example revisits Example 2 and shows that the competitive benchmark is still interior in the feasible set defined in this section and gives an example of a revenue scheme that satisfies the state-contingent constraints (8).

Example 3. Consider again the four-firm model described in Example 2, with the value function

$$v(S) = \begin{cases} 10 & \text{if } \{1, 2\} \subseteq S \text{ or } \{3, 4\} \subseteq S \\ 0 & \text{otherwise} \end{cases}$$

and the cost function $c(x_i) = x_i^2/(1 - x_i)$.

The second-best efforts $x_i = 0.411$ under the budget constraint in expected terms (7), described in Example 2, are also the solution to the constrained maximisation problem with the constraints (14). Table 1 shows that at $x_i = 0.411$, the constraints (14) are not binding except for the full set N. Therefore, the competitive benchmark, described in Example 2 is still interior in the feasible set.

One possible revenue scheme that implements the second-best efforts and satisfies the constraints (8), that total revenues given to firms in each state S do not exceed the available value $v(S)$, is

$$r_1(S) = \begin{cases} 5 & \text{if } \{1,2\} \subseteq S \text{ and } \{3,4\} \not\subseteq S \\ 2.5 & \text{if } S = N \\ 0 & \text{otherwise} \end{cases}$$

and analogously for other firms. Compared to the competitive benchmark, this scheme allows positive revenues to the firms when all technologies are invented, even though the firms' incremental contributions in that state is zero. Under this scheme, the expected profit for firm 1 is

$$5x_1x_2(1 - x_3x_4) + 2.5x_1x_2x_3x_4 - \frac{x_1^2}{1 - x_1}$$

and the equilibrium efforts are $\hat{x}_i = 0.411$ for all i, which are the second-best efforts.

5 Concluding remarks

In this paper, I analyse innovation incentives in the context of standardisation. The model introduces the research stage for multiple interacting inventions that precedes the standardisation process. It allows us to study how the value jointly created by the inventions should optimally be appropriated by their inventors and how the competitive outcome, as commonly defined, performs compared to the optimal rule. It shows that allowing supra-competitive royalties for innovators may enhance economic welfare. Specifically, it increases welfare by allowing innovators to reap more benefits when there are competing substitutes that drive the royalties down in order to compensate the suboptimal incentives that arise from complementarities. This result provides a caveat to the idea that the pre-standardisation competitive outcome optimally aligns incentives with contributions.

The effects illustrated in this paper should be interpreted as one of many relevant factors that affect the optimal innovation incentives. As technologies are assumed to generate fixed welfare that is not affected by royalties, the model isolates the problem of insufficient incentives for complementary technologies from the *multiple marginalisation* problem in licensing (also known as *royalty stacking*), whereby the cumulative royalties demanded by multiple patent holders exceed even the monopoly price (Shapiro 2001). Other known economic phenomena may counteract the effects illustrated in this paper. For example, a patent race in which multiple firms pursue the same technology can lead to over-investment in research (Tandon 1983).

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