

Standard Setting Organizations and Standard Essential Patents: Voting Power versus Market Power

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Abstract

The key finding is that Standard Setting Organizations (SSOs) choose efficient technology standards because voting power and market power have counterbalancing effects. Agents on the long side of the market have less added value in the marketplace but more voting power in cooperative organizations and conversely for the short side of the market. In a two-stage model, industry members choose technology standards by voting and then compete in the marketplace. Even when there are disagreements among vertical industry groups,

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SSO members vote for the efficient standard unanimously. When there are Standard Essential Patents (SEPs), technology adopters also vote for the efficient standard unanimously. Inventors that own SEPs will support the efficient standard under some voting rules. When there are disagreements within industry groups, SSO members choose efficient standards by majority rule. The results help explain the choice of technology standards by SSOs, the design of SSO voting rules, and the selection of SSO rules governing intellectual property (IP).

Keywords: Standards; voting; competition; technology, patents, intellectual property, Standard Setting Organizations, Standard Essential Patents

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I Introduction

Do Standard Setting Organizations (SSOs) choose efficient technology standards? To address the efficiency question requires understanding how standard setting interacts with market competition. I introduce a two-stage model in which industry members vote on standards in an SSO and compete in the market after choosing the standard. SSO members include four types of industry participants: distributors, producers, suppliers, and inventors. The relative numbers of these types of economic agents affect both voting power in the SSO and market power in competition. In the model, technology standards affect markets by changing costs, benefits, outputs, product prices, and licensing royalties. In turn, market outcomes affect voting because industry members anticipate the economic effects of standards.

The key insight of the analysis is that voting power and market power counterbalance each other. I show that SSO members vote for efficient technology standards when markets are competitive. I further show that SSO members vote for efficient standards when inventors own Standard Essential Patents (SEPs) and exercise market power in licensing.¹ When a group of industry members is larger than other

¹SEPs are patents that "read on" a standard, that is, it is necessary for adopters to license, cross license, or own patents that apply to technologies used to implement the standard.

groups, they have greater voting power but less market power, and the converse holds as well, so that SSO members choose the efficient standard. Also, when inventors exercise market power, there are incentives for inventors and technology adopters to choose the efficient standard because of the countervailing effects of voting power and market power.

The efficiency question is important because standards have major economic effects. Practically every industry operates on the basis of technology standards, some so mundane and pervasive that we tend not to notice them. For example, everyone is familiar with the number 2 pencil without considering the significance of the underlying standard. Standardization of products and business practices are critical features of most economic transactions. Standardized products include for example auto parts, electrical components, batteries, building supplies, hand tools, and paper cups. Standards are essential to contracts and pricing in financial markets including securities, derivatives, and commodity futures. Thus, the economic effects of technology standards extend far beyond a few high-profile legal cases in telecommunications.

Standards provide the coordination needed to achieve technological interoperability in many industries, as evidenced by familiar standards such as USB, LTE, WiFi, HTTP, and MP3. Standards increase market efficiency by lowering transaction costs (Kindleberger, 1983). Industries use standards for adjusting product variety, maintaining product quality and performance, measuring consistently, codifying knowledge, assuring compatibility, articulating a vision of the industry, assuring health and safety, and controlling environmental quality (Swann, 2010). Standards help promote intra-industry international trade (Swann et al., 1996). Standards developed by SSOs complement those set by market transactions and government regulations (Spulber, 2013).

SSOs affect efficiency throughout the economy, with more than one thousand organizations developing hundreds of thousands of technology standards.² SSOs involve

²There is wide range of industry-specific manufacturing standards organizations. For a directory of these organizations, see <http://www.brs-inc.com/Manufacturing/directory.asp>, accessed May 17, 2015. In addition to hundreds of specialized industry SSOs there are many general organizations that develop and distribute standards across broader industry groups. For a

many companies; for example, the American National Standards Institute (ANSI) represents more than 125,000 companies.³ SSOs provide vertical coordination among suppliers, producers and distributors in industries such as aircraft and automobiles. SSOs are important for coordination of research and development (R&D), entrepreneurship, and product innovation in many industries. For example, the European Telecommunications Standards Institute (ETSI) and the Third Generation Partnership Project (3GPP) establish standards for cellular telecommunications networks.⁴ The Institute of Electrical and Electronics Engineers (IEEE) develops standards for telecommunications, information technology, and power generation.⁵ The International Electrotechnical Commission (IEC) sets standards for electronic and electrical technologies. Various SSOs develop standards for the Internet and the "Internet of Things".⁶

The main results of the analysis are as follows. First, I show that without SEPs, SSO members unanimously choose the efficient standard. This result holds even though preferences over standards differ substantially *among* vertical industry groups. The result builds on the following intuition. Even though there are no finan-

database covering many of these groups, see Baron and Spulber (2015), For a list covering 966 industry consortia and other standards organizations and a description of their activities, see Andrew Updegrave, <http://www.consortiuminfo.org/links/#.VViiHfViko>, accessed May 17, 2015. Perinorm, which is a data base that includes a subset of standards organizations, contains 1.5 million standards documents, see http://www.normen-management.de/What-is-Perinorm/cn/cmR0bGV2ZWw9cmR0LXN0ZWNrYnJpZWYtcGVyaW5vcml0*.html, accessed May 17, 2015. IHS lists over 800,000 current and historical standards documents for more than 400 organizations, see <https://global.ihs.com/standards.cfm?> and https://global.ihs.com/individual_standards.cfm?, accessed May 17, 2015.

³ANSI is an U.S. umbrella group that includes industry organizations; see http://www.ansi.org/about_ansi/overview/overview.aspx?menuid=1, accessed May 17, 2015.

⁴ETSI includes over 800 member organizations (<http://www.etsi.org/>). 3GPP "covers cellular telecommunications network technologies, including radio access, the core transport network, and service capabilities - including work on codecs, security, quality of service - and thus provides complete system specifications. The specifications also provide hooks for non-radio access to the core network, and for interworking with Wi-Fi networks, " see <http://www.3gpp.org/about-3gpp/about-3gpp>, accessed May 7, 2015.

⁵See http://www.ieee.org/about/today/at_a_glance.html, accessed May 7, 2015.

⁶These include the World Wide Web Consortium (W3C), the Internet Engineering Task Force (IETF), the Industrial Internet Consortium (IIC), the IEC, the IEEE, ANSI, the International Telecommunication Union (ITU), and the International Organization for Standardization (ISO).

cial transfers before voting takes place, agents anticipate the effect of standards on market outcomes after standards are chosen. *Ex post* financial transfers in a competitive market equilibrium harmonize *ex ante* net benefits so that industry members consistently favor the efficient standard. This result is robust to variations in the membership composition of the SSO, different voting rules, any number of potential standards, and any sizes of the various industry groups.

Market competition induces unanimous voting for the efficient standard in part because of the countervailing effects of the size of industry groups. If the competitive market is not capacity constrained in equilibrium, marginal returns are exhausted. Then, market returns are such that the greatest number of agents are active with the most efficient standard. The returns obtained by inframarginal agents are greatest with the most efficient standards, so that all agents vote for the efficient standard.

If the competitive market is capacity constrained in equilibrium, marginal returns are positive. Then, the relative numbers of different types of economic agents affects their incremental contribution to economic value and their share of marginal returns. Economic agents that are relatively few in number have relatively less voting power in SSOs but tend to have greater market power in competition and vice versa. Agents that are relatively scarce capture economic returns at the margin and favor the efficient standard. Agents that are relatively abundant do not capture returns at the margin and so are indifferent across standards. The countervailing effects of the size of groups of economic agents imply that standards organizations will choose efficient standards and market outcomes will implement those efficient standards.

Second, I show that with SEPs, the SSO again chooses the efficient standard. In the second stage market equilibrium, I show that inventors with SEPs choose licensing offers that maximize licensing royalties. Inventors extract monopoly rents subject to industry capacity constraints and the presence of alternative existing technologies. Individual inventors will prefer those standards for which they have SEPs and will choose the standard that provides them with the greatest average returns. Inventors face a trade-off between voting power and market power, which will rule out their joining larger groups to vote for inefficient standards because that would reduce average licensing revenues. If the SSO is composed only of inventors, the SSO

can choose voting rules to deter inventors from joining smaller groups to vote for inefficient standards as a means of raising average licensing revenues. So, an SSO composed only of inventors will choose the efficient standard.

Third, I show that an SSO that includes inventors and adopters (distributors, producers, and suppliers) will choose the efficient standard. Because inventors with SEPs for a given standard capture all available incremental returns at the margin, an SSO composed only of technology adopters will choose the efficient standard unanimously. The intuition for this result is that the market equilibrium when inventors with SEPs have market power is comparable to an unconstrained competitive market in which economic rents are exhausted at the margin. As a result, technology adopters again unanimously prefer the efficient standard. If the SSO is composed of both technology adopters and inventors, the unanimous choice of efficient standards by adopters allows the SSO to use less restrictive voting rules such that inventors and adopters choose the efficient standard. In addition, the analysis shows that the choice of an efficient standard is robust to whether or not the SSO has rules that limit *ex post* licensing revenues for SEPs.

Fourth, I consider disagreements about standards *within* industry groups. When there is disagreement about standards within a group of distributors, producers, or suppliers, that group will no longer support a standard unanimously. This is because even though markets involve transfers among industry groups, they usually do not involve transfers within industry groups. I show instead that when there are disagreements within a group, a majority of the group always supports the efficient standard. The reason for this result is that efficient standards increase the number of active members of the group at the market equilibrium in comparison to other standards, generating greater support for the efficient standard. Combined with the previous result showing unanimity when there is agreement within industry groups, the analysis implies that SSOs will have different voting rules based on the extent of disagreements within industry groups. The voting rules also approach a consensus depending on the extent of the innovation represented by the efficient standard. This analysis helps explain why SSO rules vary along a spectrum from majority voting to full consensus.

Fifth, I compare the choice of a technology standard that requires SEPs with a technology standard that does not require SEPs. There is a trade-off between the quality of the standard with SEPs and the cost of patent license royalties. To address this trade-off, I define a high-quality standard as a *drastic innovation*, extending Arrow's (1962) term for individual inventions to technology standards. A new technology standard represents a drastic innovation if and only if total royalties for the SEPs that apply to the standard are not constrained by a royalty based on a benchmark standard. I obtain the result that with drastic innovations, technology adopters will choose an efficient standard with SEPs even if the alternative standard has no SEPs. With drastic innovations, there is no need for the SSO to regulate *ex post* royalties and less need for adopters of inventions to participate in SSOs to balance the influence of inventors. Conversely, in industries with nondrastic innovations, there is a greater need for participation by many industry groups to regulate royalties and counter the influence of inventors.

Finally, I explore some of the empirical implications of these results. The model addresses several fundamental institutional features of technology standards: *voting* on standards, *bargaining* over patent licenses, and *interaction* between standard setting and market competition. Most SSOs choose standards by voting (Goerke and Holler, 1995; Baron and Spulber, 2015). The present results help explain why specific voting rules are observed and also how these rules may vary across SSOs and also vary within particular SSOs over time. The voting rules and membership of SSOs are observable so it is possible to consider empirically the relationship between voting rules and SSO membership.

Theoretical models of SSOs generally have not considered voting. An important exception is the contribution of Goerke and Holler (1995) that focuses on the coordination function of standard setting. They consider the choice between two product standards by two groups of buyers. The buyers benefit from selecting a standard because of network effects even though each group would prefer a different standard. Goerke and Holler (1995) examine voting as a way of addressing multiple Nash equilibria in standards adoption. In their model, a supermajority voting rule is necessary to induce the standards organization to choose an efficient standard.

The present model differs from their analysis by considering a market equilibrium after standards are chosen that generates transfers among economic agents. This yields additional results on voting rules when there are disagreements both within and among industry groups. The literature on public goods has considered mixed models in which individuals simultaneously vote on the provision of public goods and engage in market transactions.⁷

In practice, patent licensing involves bargaining between owners of intellectual property (IP) and technology adopters (Spulber, 2016). The present model shows that standards are efficient even if inventors licensing SEPs extract monopoly rents. Bargaining between IP owners and technology adopters does not necessarily involve multiple marginalization as is observed in models of posted prices. The results suggest that in practice SEPs will not generate multiple marginalization and will be consistent with inclusion of many SEPs in inputs and products conforming to a technology standard. The analysis also helps explain variations in SSO rules governing IP disclosure and patent licensing.

Because it considers offers of patent licensing agreements and equilibrium market pricing of royalties, the present analysis differs from models of SEPs in which inventors determine licensing royalties by posting prices. In posted price models, industry participants choose prices that exceed the bundled monopoly level due to free rider effects, see Schmalensee (2009), Lévêque and Ménière (2011), Llanes and Poblete (2014), and Lerner and Tirole (2015). Lerner and Tirole (2015) associate patented technological features with standards and provide conditions under which adopters and inventors choose inefficient technology standards. These studies do not examine voting on standards.

An important implication of the present analysis is that technology standards are an indication of innovation. The incremental effects of the technology standard provide a measure of the effects of the innovation associated with the standard. This is a particularly useful implication of the analysis when a standard has different ef-

⁷On such mixed voting and market models of public goods, see particularly Bowen (1943), Slutsky, (1977), Denzau and Parks (1983), and Greenberg and Shitovitz (1988). On dividing a pie by voting, see for example Rosenthal (1975) and Greenberg (1979).

fects on the various industry groups, such as suppliers, producers, and distributors. This measure of innovation also is useful when complex innovations combine multiple inventions. The standard spells out many technological specifications for both performance and interoperability and in this way provides a summary of the overall innovation.

By indicating the quality of the innovation, determining how a standard affects market outcomes may be useful for empirical analysis. Although the efficiency of standards may not be observable directly, it is possible to observe the conformity of market outcomes with technology standards, including the development of products that include multiple SEPs. The voting rules and IP policies of SSOs also can be useful in understanding how the quality of the innovation interacts with the SSOs' choices of technology standards.

The efficiency of standards observed in the present analysis has implications for antitrust policy towards SSOs and IP. It is often argued that dominance of the SSO by particular interest groups affects the choice of standards.⁸ The main results obtained here suggest instead that the choice of technology standards is efficient for any combination of groups of suppliers, producers, and distributors. Also, the discussion shows that even in the worst case scenario, when inventors with SEPs exercise market power after standards are chosen, SSOs choose efficient standards. The results also help explain why final consumers need not participate in SSOs for outcomes to be efficient.

The results shed some light on why SSOs generally engage in decision making without *ex ante* financial transfers, primarily using voting and discussion in committees. The combination of voting and market competition helps clarify the distinction between voting power and market power. Because there are no *ex ante* transfers, the voting power of players (political power) differs from coalitional power in cooperative games (economic value) as Barry (1980a, 1980b) points out.⁹ It is therefore possible to distinguish between voting power in the SSO and market power after standards

⁸On the role of technology standards in public policy, see Greenstein and Stango (2012).

⁹Barry (1980a, 1980b) distinguishes measures of voting power without transfers from measures such as those in Shapley and Shubik (1954) that are based on voting as a contribution to coalitions.

are established. However, when SSOs choose technology standards, markets create *ex post* transfers, which explains why it is fruitful to consider the interactions between cooperative standard setting and market competition.

The paper is organized as follows. Section II presents the basic two-stage model of standard setting and market competition. Section III characterizes the equilibrium choice of a technology standard and the resulting market equilibrium prices. Section IV extends the analysis to the choice of a standard when inventors have SEPs. Section V extends the analysis to consider disagreements about standards within vertical industry groups. Section VI discusses some empirical and public policy implications and Section VII concludes the discussion.

II The basic framework

This section develops a two-stage model of the interaction between a standards organization and market competition. In the first stage of the model, the members of the standards organization engage in voting to choose a technology standard. In the second stage of the model, inventors offer licenses for SEPs, industry groups (distributors, producers, and suppliers) apply the technology standard, and royalties and prices are realized at the market equilibrium. The model will be solved by backward induction.

II.1 The industry

Consider an industry with three vertically differentiated groups consisting of distributors, producers, and suppliers. Distributors denote marketers, wholesalers, retailers, original equipment manufacturers (OEMs), and service providers who sell to final consumers. Producers include manufacturers, assemblers, and supply chain managers. Suppliers include providers of materials, parts, components, software, services, and other primary inputs. This framework allows the study of how the allocation of economic rents across vertical levels of the industry affects voting in

standards organizations. The discussion extends readily to many industry groups. The discussion also allows vertically integrated industry groups; for example, producers and suppliers may be vertically integrated.

There is a set of potential technology standards $S = \{s_1, s_2, \dots, s_T\}$. The standards $s \in S$ are not necessarily in any order and represent complex multi-dimensional technologies or qualitative descriptions of technologies. Standards are specifications that affect product quality and interoperability of parts and components. Standards apply to inputs, components, and final products and affect production costs and consumer benefits. Participation in the standards organization generates benefits from coordination.¹⁰

Assume that distributors, producers, and suppliers have unit capacity. This setting helps illustrate how the relative numbers of agents determine the outcome of competition in the market, with the short side of the market generally having greater value at the margin and the long side of the market generally having less value at the margin. At the same time, this setting illustrates how the relative numbers of agents affect participation and voting power in the standards organization. This allows us to observe how agent participation affects incremental value in the marketplace and affects voting power in the standards organization.

Distributor types i are uniformly distributed on the interval $[0, I]$. Let $u_i(s) = u(s) - \eta(i) > 0$ represent consumer benefits net of distribution costs for consumers served by a type i distributor. Assume for ease of presentation that distributors obtain all consumer benefits net of distribution costs. The results also hold if distributors obtain only a share of consumer benefits or if there are no distributors and consumers retain all of their benefits. Producer types h are uniformly distributed on the interval $[0, H]$ and producer costs are $c_h(s) = c(s) + \theta(h)$. Supplier types j are uniformly distributed on the interval $[0, J]$ and supplier costs are $k_j(s) = k(s) + \zeta(j)$.

Assume that the functions $\eta(i)$, $\theta(h)$, and $\zeta(j)$ are differentiable and increasing for any $s \in S$. Notice that there is agreement about the effects of standards *within*

¹⁰The returns to coordination are implicit in the benefits of the suppliers, producers and distributors. For the purposes of the present analysis, it is not necessary to specify explicitly the sources of coordination benefits such as economies of scale, network effects, or transaction efficiencies.

each industry group. A later section considers disagreements about the effects of standards within industry groups. Such disagreements have important consequences for SSO voting rules.

I do not impose ordering restrictions on how standards affect $u(s)$, $c(s)$, or $k(s)$. This allows there to be disagreements about the effects of standards *among* groups of distributors, producers, and suppliers.¹¹ Such preferences can generate voting paradoxes of the type identified by Condorcet (1976) and Arrow (1951). As we will see however, the preferences of economic agents are modified by anticipation of market-mediated transfers after standard setting occurs.

Let q denote industry output. Because all agents have unit capacity, the size of the smallest industry group gives an industry capacity constraint

$$\bar{q} = \min\{H, I, J\}. \tag{1}$$

The capacities of the three industry groups are strictly complementary in the production of the final industry output. If the industry capacity constraint is not binding, economic rents are exhausted at the margin and no group has market power. If the industry capacity constraint is binding, then the scarce group has market power and captures rents at the margin. The framework is sufficiently general that it includes both the presence or absence of market power at the margin.

For ease of presentation, assume that the sizes of each industry group differ, $H \neq I \neq J$. This implies that when the industry capacity constraint is binding, the scarce group captures economic rents at the margin due to competition among members of the other groups. If two or more categories of economic agents are of equal size, market prices depend on relative bargaining power, which determines the allocation of rents at the margin. This in turn affects the allocation of rents across industry groups. However, I show in the Appendix that this restriction does not change the results.

Market equilibrium prices are determined by competition among distributors,

¹¹For example, with three standards, a distributor may have benefits such that $u(s_1) > u(s_2) > u(s_3)$, a producer may have costs such that $c(s_2) < c(s_3) < c(s_1)$, and a supplier may have costs such that $k(s_3) < k(s_2) < k(s_1)$.

producers, and suppliers. The output price is $p(s)$ and the input price is $r(s)$. The market equilibrium industry output q^0 determines the marginal agents for each industry group. Given market equilibrium prices, it follows that active distributors have profits

$$v_i(s) = u_i(s) - p(s), \quad i \in [0, q^0]. \quad (2)$$

Active producers have profits

$$\pi_h(s) = p(s) - r(s) - c_h(s), \quad h \in [0, q^0]. \quad (3)$$

Active suppliers have profits

$$g_j(s) = r(s) - k_j(s), \quad j \in [0, q^0]. \quad (4)$$

An agent is active only if it has non-negative profits, and inactive agents have zero profits.

The economic effects of the technologies that make up a standard s are new to the market, so they constitute an innovation in the sense of Schumpeter. I refer to the incremental net benefits of the standard $\varphi(s)$ as the *quality of the innovation*,

$$\varphi(s) \equiv u(s) - c(s) - k(s). \quad (5)$$

Let $\psi(q)$ denote the incremental costs of output evaluated at the marginal distributor, producer and seller,

$$\psi(q) \equiv \eta(q) + \theta(q) + \zeta(q). \quad (6)$$

Notice that the incremental costs of output are increasing, $\psi'(q) = \eta'(q) + \theta'(q) + \zeta'(q) > 0$. For ease of discussion, let all standards be feasible, $u(s) - c(s) - k(s) > \psi(0)$.

The total profits distributors are $V(s, q) = \int_0^q v_i(s) di$, which also measures consumer benefits net of distributor costs. The total profits of producers are $\Pi(s, q) = \int_0^q \pi_h(s) dh$ and those of suppliers are $G(s, q) = \int_0^q g_j(s) dj$. Social welfare equals

$W = V(s, q) + \Pi(s, q) + G(s, q)$ so that

$$W = \int_0^q u_i(s) di - \int_0^q c_h(s) dh - \int_0^q k_j(s) dj. \quad (7)$$

It follows that we can write social welfare as a function of the quality of the innovation and output, $W(\varphi(s), q) = \varphi(s)q - \int_0^q \psi(x) dx$. The effect of output on social welfare equals the difference between the quality of the innovation and incremental output costs,

$$\frac{\partial W(\varphi(s), q)}{\partial q} = \varphi(s) - \psi(q). \quad (8)$$

Let s^* and q^* maximize social welfare $W(\varphi(s), q)$ subject to the industry capacity constraint, $q \leq \bar{q}$. Social welfare is strictly concave in output, $\frac{\partial^2 W(\varphi(s), q)}{\partial q \partial q} = -\psi'(q) < 0$. This implies that there is a unique output \hat{q} that maximizes social welfare without the capacity constraint, $\varphi(s) - \psi(\hat{q}) = 0$. We can write the unconstrained optimal output as a function of the quality of the innovation, $\hat{q} = \hat{q}(\varphi(s))$. The unconstrained optimal output is strictly increasing in the quality of the innovation, $\frac{d\hat{q}(\varphi(s))}{d\varphi(s)} = \frac{1}{\psi'(\hat{q}(\varphi(s)))} > 0$.

The efficient industry output for any standard s is a function of the quality of the innovation and the industry capacity constraint,

$$q^*(\varphi(s), \bar{q}) = \min\{\hat{q}(\varphi(s)), \bar{q}\}. \quad (9)$$

It follows that industry output $q^*(\varphi(s), \bar{q})$ exists and is unique for any standard s . Because the set of standards is finite, there exists an efficient standard s^* . Assume that the efficient standard s^* is unique. This implies that the efficient output level $q^* = q^*(\varphi(s), \bar{q})$ is unique as well.

II.2 Inventors and SEPs

Suppose that there is a set of inventors $y \in [0, Y]$, each of whom owns a patent portfolio. Inventors' patent portfolios include SEPs that apply to one or more standards.¹² The potential adopters of the SEPs are distributors, producers, and suppliers. Issues related to patent validity, infringement, or enforcement are beyond the scope of the present discussion.

To represent SEPs, let $\lambda : [0, Y] \times S \rightarrow \{0, 1\}$ be an indicator function such that $\lambda_s(y) = 1$ if inventor y has patents that are essential for standard s and $\lambda_s(y) = 0$ otherwise. This setting is sufficiently general that it can represent any association of inventions and standards. The number of inventors with SEPs applying to the standard s is given by

$$N(s) = \int_0^Y \lambda_s(y) dy. \quad (10)$$

The industry must adopt the SEPs of all $N(s)$ inventors to implement the standard s . Define $Y(s) \subseteq [0, Y]$ as the set of inventors $\{y : \lambda_s(y) = 1\}$, that is, the set of inventors with SEPs for standard s .

After the standard s is chosen by the SSO, each inventor y with SEPs for standard s makes a binding commitment to supply patent licenses to each adopter that demands a license up to a maximum number of licenses x_y . Each technology adopter purchases one license from each inventor with SEPs for the standard. Let q_y denote the total number of patent licenses for invention y demanded by technology adopters. So, each inventor offers a license schedule $X_y(q_y)$ given by

$$X_y(q_y) = \min\{q_y, x_y\}. \quad (11)$$

For ease of notation, I refer to the license schedule by the maximum number of

¹²In practice, there is an imperfect match between patents and standards because inventors declare their patents to be essential to particular standards. Inventors may have incentives to incorrectly declare their patents as essential to avoid legal penalties or to obtain licensing royalties. Some SSOs providing limited monitoring of what patents inventors declare as essential. Baron and Pohlmann (2015) provide an extensive mapping of patents to technology standards that helps to analyze the connection between standards and SEPs.

licenses offered x_y . When making license schedule offers, inventors do not know the license schedule of others inventor, the number of adopters that demand licenses, or downstream market output. I consider weakly dominant strategy equilibria in license offers.

After inventors offer license schedules, adopters choose license demands. Technology adopters must license all the SEPs for a given standard. Any or all groups of distributors, producers, or suppliers are technology adopters that pay licensing fees to inventors with SEPs that apply to a particular standard. In practice, a particular patent can be licensed only at one vertical level of the industry. However, there may be SEPs at multiple industry levels because technologies differ among inventors and also because individual inventors can have multiple technologies in their portfolios. Even if different SEPs are required at different vertical levels of production, the SEPs for a particular standard are strict complements for the industry. This implies that industry output cannot exceed the minimum of the maximum license offers,

$$q \leq \min\{x_y : y \in Y(s)\}.$$

With licensing royalties $\rho^I(s)$, $\rho^H(s)$, and $\rho^J(s)$ obtained from each vertical level of the industry, the profits of producers, distributors, and suppliers are $\pi_h(s) = p(s) - r(s) - c_h(s) - \rho^H(s)$, $v_i(s) = u_i(s) - p(s) - \rho^I(s)$, and $g_j(s) = r(s) - k_j(s) - \rho^J(s)$. Because licensing costs are passed through to consumers, there is no need to distinguish between licensing fees for distributors, producers, or suppliers. So, we can let $\widehat{\rho}(s) = \rho^I(s) + \rho^H(s) + \rho^J(s)$ represent total licensing royalties per unit of output for SEPs that are associated with a given standard s .

The market equilibrium establishes total licensing royalties. At the market equilibrium when the industry capacity constraint is not binding, the marginal agents are such that $\pi_q(s) = v_q(s) = g_q(s) = 0$ so that

$$\widehat{\rho}(s) = (u_q(s) - p(s)) + (p(s) - r(s) - c_q(s)) + (r(s) - k_q(s)). \quad (12)$$

So, at the market equilibrium, marginal benefits equal total royalties per unit of

output,

$$\widehat{\rho}(s) = \varphi(s) - \psi(q). \quad (13)$$

When the industry capacity constraint is binding, this also holds because the number of licenses equals the capacity constraint. The unequal sizes of industry groups imply that two industry groups are larger than the capacity constraint and bid for licenses. So, $\widehat{\rho}(s) = \varphi(s) - \psi(q)$ applies whether or not the industry is capacity constrained, $q \leq \bar{q}$.

Total profits for the bundle of inventions $R = \widehat{\rho}(s)q$ can be written as a function of the quality of the innovation and industry output,

$$R(\varphi(s), q) = (\varphi(s) - \psi(q))q. \quad (14)$$

Assume that total royalties are evenly divided among inventors with SEPs that apply to a particular standard s .¹³ This simplifies the discussion although the analysis can be extended readily to allow bargaining with uneven division.¹⁴ Let $\xi_y(s, q)$ denote licensing revenues for an inventor y when output equals q and the standard is s ,

$$\xi_y(s, q) = \frac{R(\varphi(s), q)\lambda_s(y)}{N(s)}, \quad (15)$$

for all $y \in [0, Y]$ and $s \in S$.

Assume that the SSO places an upper limit on royalties for each SEP, $\frac{\widehat{\rho}(s)}{N(s)} \leq \frac{\bar{p}}{N(s)}$. We can express the SSO's upper limit on total royalties as a lower limit on output, $q \geq q_\mu$, where

$$q_\mu \equiv \widehat{q}(\mu\varphi(\bar{s}) + (1 - \mu)\varphi(\bar{s})). \quad (16)$$

Recall that $\widehat{q}(\cdot)$ is the inverse of $\psi(q)$. For the outcome to be feasible, assume that the lower output constraint is less than industry capacity, $q_\mu < \bar{q}$. The SSO policy constraint is defined as follows. First, suppose that there is an existing technology

¹³Each inventor with SEPs for a particular standard obtains an equal share, so it is not necessary to consider the number of patents in the inventor's portfolio.

¹⁴On bargaining, see Edgeworth (1881), Shapley (1952), Aumann (1987), Aumann and Shapley (1974), and Shubik (1982, 1984).

standard $\tilde{s} \neq s^*$ that is based on available in the market without licensing costs, $\hat{\rho}(\tilde{s}) = 0$. This is a default technology is available *ex post*, that is after the standard is chosen. So, distributors, producers, and suppliers can use the existing technology to follow the default standard. This implies that unconstrained total market royalties cannot exceed the incremental benefits of the new standard. If $\varphi(s) \geq \varphi(\tilde{s})$, inventors face a constraint on royalties reflecting improvements in the incremental effects of the standard, $\hat{\rho}(s) \leq \varphi(s) - \varphi(\tilde{s})$.

Second, the SSO chooses a benchmark standard $\bar{s} \in S$ that is only available *ex ante*, that is before the SSO chooses the standard. Suppose that the benchmark standard is better than the default standard, $\varphi(\bar{s}) > \varphi(\tilde{s})$. Let $\mu \in [0, 1]$ be a policy parameter that represents the strictness of SSO controls on royalties. The upper limit on royalties is given by a weighted average of the incremental contributions of the standard in comparison to the default standard and the benchmark standard,

$$\bar{\rho}(s, \mu) = \mu[\varphi(s) - \varphi(\bar{s})] + (1 - \mu)[\varphi(s) - \varphi(\tilde{s})]. \quad (17)$$

So, $\bar{\rho}(s, \mu) = \varphi(s) - \mu\varphi(\bar{s}) - (1 - \mu)\varphi(\tilde{s})$, which gives q_μ . If $\mu = 0$, the SSO does not restrict royalties. The greater is the value of the policy parameter μ , the stricter is the SSO's constraint on royalties, $\frac{\partial \bar{\rho}(s, \mu)}{\partial \mu} = \varphi(\tilde{s}) - \varphi(\bar{s}) < 0$.

As a benchmark, consider the profit-maximization problem of a monopoly inventor that offers the entire *bundle* of SEPs for a particular standard s ,

$$\max_q R(\varphi(s), q) \text{ subject to } q_\mu \leq q \leq \bar{q}.$$

Let $\hat{q}^M(\varphi(s))$ denote the unconstrained profit maximizing output. Assume that the unconstrained profit-maximizing output is unique and satisfied the first order condition,

$$\varphi(s) - \psi(q) - \psi'(q)q = 0. \quad (18)$$

If the monopoly output is not unique, let \hat{q}^M represent the smallest profit-maximizing output. This is for ease of notation and without loss of generality. If the solution is not unique, I will show that the equilibrium equals the smallest profit-maximizing

output.

The profit-maximizing output depends on the quality of the innovation and the upper and lower limits on output, $q^M = q^M(\varphi(s), q_\mu, \bar{q})$, where $q^M = \hat{q}^M$ for $q_\mu \leq \hat{q}^M \leq \bar{q}$. The bundled monopoly licensing revenues can be expressed as a function of the quality of the innovation, the SSO policy parameter, and industry capacity,

$$R^M(\varphi(s), q_\mu, \bar{q}) = R(\varphi(s), q^M(\varphi(s), q_\mu, \bar{q})). \quad (19)$$

II.3 Voting in the standards organization

The SSO selects a standard on the basis of voting by its members. The members of the SSO vote simultaneously on the standards in the set S and each member votes for only one standard. Members of the organization vote as individuals not in voting blocs.

In evaluating standards, industry members anticipate the market equilibrium that would be observed after the standard is chosen. So, the functions $v_i(s)$, $\pi_h(s)$, and $g_j(s)$ represent market-mediated preferences over the set of standards of distributors, producers, and suppliers respectively. Assume that if an economic agent is indifferent between standards s and s^* , the agent chooses the efficient standard.

One or more industry groups are members of the standards organization. Define the sets of distributors, producers, and suppliers by $F_I = [0, I]$, $F_H = [0, H]$, and $F_J = [0, J]$. The sets consisting of the union of two industry groups are $F_{H,I}$, $F_{H,J}$, and $F_{I,J}$ and the full set of industry participants is $F_{H,I,J}$. Let Λ denote the possible membership sets of the standards organization excluding inventors,

$$\Lambda = \{F_H, F_I, F_J, F_{H,I}, F_{H,J}, F_{I,J}, F_{H,I,J}\}. \quad (20)$$

Let $F_Y = [0, Y]$ denote the set of inventors with SEPs. When there are inventors with SEPs, the set F of members of the organization can consist of either adopters $F \in \Lambda$, inventors $F = F_Y$, or both inventors and adopters $F = F_Y \cup F'$ where $F' \in \Lambda$.

Define the voting game by $g(\delta; F)$. The set F refers to the members of the organization, all of whom participate in voting. The organization chooses a standard only if the proportion of votes for that standard exceeds the decision rule δ , where $0 \leq \delta \leq 1$. If $\delta \leq 1/2$, ties are resolved in favor of the efficient standard.

II.4 Timing

The equilibrium of the two-stage game is as follows.

1. In stage one, the standards organization chooses a standard $s^0 \in S$ according to the voting game $g(\delta; F)$. Depending on whether or not they are members of the SSO, distributors, producers, and suppliers vote for the standard that maximizes their respective net benefits, $v_i(s)$, $\pi_h(s)$, and $g_j(s)$.

2. In stage two, after the standard is established, distributors, producers, and suppliers transact in the market given the standard s^0 . Market competition determines equilibrium output $q^0(s)$ and prices $p(s^0)$ and $r(s^0)$.

When there are inventors with SEPs, the two-stage game is modified as follows.

1. In stage one, the standards organization chooses a standard $s^0 \in S$ according to the voting game $g(\delta; F)$. Depending on whether or not they are members of the SSO, inventors and technology adopters (distributors, producers, suppliers) vote for the standard $s^0 \in S$ that maximizes their respective net benefits $v_i(s)$, $\pi_h(s)$, $g_j(s)$, and $\xi_y(s, q)$.

2. In stage two, $N(s^0)$ inventors with SEPs that apply to the standard $s^0 \in S$ offer licenses x_y to potential technology adopters and adopters determine their demand for licenses, q_y . Market competition determines equilibrium output $q^0(s^0)$, total royalties $\rho(s^0)$, and prices $p(s^0)$, $r(s^0)$.

III The technology standard without SEPs and disagreement among industry groups

This section considers the SSO's choice of a technology standard when there are no SEPs. SSO members vote on the standard in anticipation of its effects on the market equilibrium. The market equilibrium depends on the choice of the technology standard by the SSO. The game is solved by backward induction. The proofs of the main results are given in the appendix.

III.1 The competitive market equilibrium

The market equilibrium is perfectly competitive when there are no SEPs. This provides a benchmark for the later discussion of the market equilibrium when there are SEPs. As would be expected, the competitive market equilibrium output equals the efficient output for any standard s , $q^0 = q^*(\varphi(s), \bar{q})$. The market equilibrium output and market participation by industry groups depend on the equilibrium standard.

If the industry is not capacity constrained, marginal producers, distributors, and suppliers have zero profits and prices are given by

$$u(s) - \eta(q) = p(s) = c(s) + \theta(q) + r(s), \quad (21)$$

$$r(s) = k(s) + \zeta(q). \quad (22)$$

It follows that economic rents are exhausted at the margin, $\varphi(s) = \psi(\hat{q})$.

When the market equilibrium is capacity constrained, economic rents are positive at the margin, $\varphi(s) > \psi(\bar{q})$. Prices depend on the relative numbers of producers, distributors, and suppliers. The members of the relatively abundant industry groups engage in competitive bidding or Bertrand price competition.¹⁵ The members of the scarce industry group have market power and capture economic rents at the margin. The market equilibrium with capacity constraints also is related to Makowski's

¹⁵The allocation of economic rents at the margin is related to the "method of marginal pairs" of Böhm-Bawerk (1891). See Spulber (2006) for additional discussion.

(1980a) and Ostroy's (1980) characterization of a competitive equilibrium using the "no surplus" condition.¹⁶

There are three capacity-constrained market equilibria. (i) If distributors are in the scarce category, $\bar{q} = I < \min\{H, J\}$, market equilibrium prices depend on marginal costs of input supply and production at the industry output, $p(s) = c(s) + \theta(\bar{q}) + k(s) + \zeta(\bar{q})$ and $r(s) = k(s) + \zeta(\bar{q})$. (ii) If producers are in the scarce category, $\bar{q} = H < \min\{I, J\}$, the market equilibrium output price equals marginal consumer benefits, $p(s) = u(s) - \eta(\bar{q})$, and the input price equals the marginal cost of input supply, $r(s) = k(s) + \zeta(\bar{q})$. (iii) Finally, if suppliers are in the scarce category, $\bar{q} = J < \min\{H, I\}$, the market equilibrium output price depends on marginal consumer benefits $p(s) = u(s) - \eta(\bar{q})$ and the input price equals marginal consumer benefits net of marginal production costs, $r(s) = u(s) - \eta(\bar{q}) - c(s) - \theta(\bar{q})$.

III.2 The equilibrium technology standard with disagreement among industry groups

The relative numbers of agents in each industry group affect the potential number of votes for technology standards in the standards organization. The members of the standards organization vote on standards taking into account the effects of the standard on their net benefits at the market equilibrium. As shown in the preceding discussion, the relative numbers of economic agents in each industry group also affect the allocation of economic rents at the market equilibrium. The equilibrium standard thus depends on how the relative numbers of agents in each industry group affect both the choice of standards and market outcomes.

Given the efficient industry output, we can write social welfare as a function of the quality of the innovation,

$$w(\varphi(s)) = \varphi(s)q^*(\varphi(s), \bar{q}) - \int_0^{q^*(\varphi(s), \bar{q})} \psi(x)dx. \quad (23)$$

¹⁶An allocation satisfying the "no surplus" condition allocates to each individual their contribution to total surplus in the economy. See Makowski (1983), Ostroy (1984), and Makowski and Ostroy (1995).

By the envelope theorem, it follows that social welfare is strictly increasing in the quality of the innovation, $w'(\varphi(s)) = q^*(\varphi(s), \bar{q}) > 0$.

This implies that a standard s^* maximizes social welfare $w(\varphi(s))$ over S if and only if it maximizes the quality of the innovation $\varphi(s)$ over S . This is a useful observation because the innovations represented by $\varphi(s)$ are important in determining individual agents' votes for standards.

Although the market equilibrium may depend on the relative numbers of agents in each group, I show that the organization's choice of an equilibrium standard does not depend on the relative numbers of agents in each group. The standards organization chooses the efficient standard unanimously because *ex post* market equilibrium transfers coordinate distributor, producer, and supplier preferences so that they agree on the choice of the efficient standard. The main result of the analysis is as follows.

PROPOSITION 1. *Without SEPs, for any sizes H, I, J of the industry groups, any number of standards T , any membership set $F \in \Lambda$, and any decision rule δ , the members of the standards organization unanimously choose the efficient standard $s^0 = s^*$.*

Proposition 1 shows that the allocation of economic rents at a competitive market equilibrium is sufficient to induce members of a standards organization to vote for the efficient standard. The intuition for the result is as follows. If the market equilibrium is not capacity constrained, equilibrium prices exhaust marginal net benefits. Economic agents thus benefit from having the greatest quality of the innovation. Because the profits of any agent depend on the quality of the innovation, rather than on the effect of the standard on their own benefits or costs, all agents will prefer the efficient standard.

The result continues to hold even if the market equilibrium is capacity constrained. Even if a group of agents has market power after the standard is chosen, this does not translate into voting power in the standards organization. If a group of agents is relatively scarce, its members obtain all marginal net benefits at the market equilibrium. Therefore, the members of the relatively scarce group prefer the efficient standard. If a group of agents is relatively abundant at the market equilibrium, its

members do not obtain a share of marginal net benefits at the market equilibrium. Therefore, members of groups that are relatively abundant at the market equilibrium are indifferent between technology standards and therefore choose the efficient standard.

Proposition 1 demonstrates that with market competition after standard setting, market power counterbalances voting power. It should be emphasized that there is no assumption on how standards affect distributor utility, producer costs or supplier costs. This means that suppliers, producers, and distributors may rank standards in a similar way or very differently in terms of their respective utility or costs. However, the result shows that the preferences of agents over standards are affected instead by the surplus they receive at the market equilibrium. The market equilibrium affects the allocation of surplus to the various industry groups. The market equilibrium generates efficient standards, whether or not industry groups capture returns at the margin.

Although voting on standards potentially depends on the relative numbers of agents in various groups, the market effects of the relative numbers of agents enhance coordination within the standards organization. Because the efficient standard is chosen unanimously, it follows that the result is robust to whether any one or two or all three groups participate in the standard-setting process. This suggests that even if a standards organization does not have representation by a particular industry group, it will have an incentive to choose the efficient standard. Because markets determine rent transfers, unanimity is preserved without only some groups participating.

This also suggests that consumer representatives need not participate in the SSO to generate a welfare maximizing outcome. Suppose that instead of distributors, final consumers have utility $u_i(s)$ and do not participate in the SSO. Then, participation only by input suppliers and producers would be sufficient for the SSO to select the efficient standard unanimously.

Because voting is unanimous, the result is robust to majority, relative majority, and super-majority voting. In addition, the result also suggests that industries with multiple organizations may choose the same standards. In practice, some standards organizations adopt or incorporate the standards of other organizations. Many

standards organizations are able to operate effectively with super-majority voting rules and appear to operate by consensus. In later sections, I consider conditions under which consensus may not be achieved.

Voting on standards combined with a competitive market equilibrium after the standard is chosen leads to an efficient market outcome.

PROPOSITION 2. *The market equilibrium output is efficient, $q^0 = q^*(\varphi(s^*), \bar{q})$. The equilibrium standard s^* maximizes the market equilibrium output $q^*(\varphi(s), \bar{q})$ and the total profits of distributors $V(s, q^*(\varphi(s), \bar{q}))$, producers $\Pi(s, q^*(\varphi(s), \bar{q}))$, and suppliers $G(s, q^*(\varphi(s), \bar{q}))$ over the set of standards S .*

This result shows that voting on standards and market competition generate the efficient outcome. In equilibrium, the technology standard and industry output maximize social welfare.

IV The technology standard with SEPs

This section extends the basic model to consider standard setting when inventors have SEPs. The standards organization potentially includes technology adopters (distributors, producers, suppliers) and inventors. In the first stage of the model, the members of the SSO vote to choose a technology standard. In the second stage of the model, inventors with SEPs for the standard choose licensing royalties offered to technology adopters. Then, adopters apply the technology standard and compete in the market.

IV.1 The market equilibrium and efficiency with SEPs

After the standard is chosen, inventors offer license schedules $X_y(q_y) = \min\{q_y, x_y\}$ to technology adopters who then choose license demands. The characterization of the equilibrium applies reasoning developed in Spulber (2015, 2016).

PROPOSITION 3. *There exists a unique weakly dominant strategy equilibrium in license offers, $x_y^0, y \in Y(s)$. For any given standards, the equilibrium maximum*

license offers are equal to the bundled monopoly output $x_y^0 = q^M(\varphi(s), q_\mu, \bar{q})$ and equilibrium industry output equals the bundled monopoly output $q^0 = q^M(\varphi(s), q_\mu, \bar{q})$.

Proposition 3 shows that inventors with SEPs choose the joint-profit maximizing outcome even though they choose license offers non-cooperatively. Inventors with SEPs obtain monopoly profits subject to limitations from SSO royalty constraints. The intuition for this result is that inventors take into account the effects of their license offers on the market outcome. The monopoly output is the unique weakly dominant strategy because if other inventors choose maximum offers above the monopoly level, an inventor would have an incentive to choose a maximum offer at the monopoly level. Conversely, if other inventors choose maximum offers below the monopoly level, an inventor would be indifferent between an offer at the monopoly level and any offer above the lowest of the other offers.

Proposition 3 shows that the equilibrium license offers eliminate multiple marginalization. The efficiency of the licensing differs the outcome in which inventors choose royalties by posting prices noncooperatively, such as the Cournot (1838) complementary monopolies model. In practice, patent licensing usually involves bargaining rather than posted prices; see Spulber (2016) and the references therein.

Proposition 3 implies that licensing revenues for any inventor y can be written using monopoly revenues,

$$\xi_y(s, q_\mu, \bar{q}) = R^M(\varphi(s), q_\mu, \bar{q}) \frac{\lambda_s(y)}{N(s)}, \quad (24)$$

for all $y \in [0, Y]$ and $s \in S$. Second-best social welfare, which is social welfare evaluated at the monopoly output, depends on the quality of the innovation,

$$w^M(\varphi(s), q_\mu, \bar{q}) \equiv W(\varphi(s), q^M(\varphi(s), q_\mu, \bar{q})). \quad (25)$$

This can be shown to imply that the first-best technology standard also maximizes second-best social welfare. This result will be useful in evaluating the choice of the technology standard with SEPs.

PROPOSITION 4. *The first-best technology standard s^* is the unique standard*

that maximizes inventors' monopoly revenue $R^M(\varphi(s), q_\mu, \bar{q})$ and also is the unique standard that maximizes second-best social welfare $w^M(\varphi(s), q_\mu, \bar{q})$.

Based on the efficiency of the standard, we can characterize the effects of the standard on output and profits.

PROPOSITION 5. *The market equilibrium output at the efficient standard s^* is greater than or equal to that with other standards, $q^M(\varphi(s^*), q_\mu, \bar{q}) \geq q^M(\varphi(s), q_\mu, \bar{q})$ for $s \neq s^*$, $s \in S$. The equilibrium standard s^* maximizes the total profits of distributors $V(s, q^M(\varphi(s), q_\mu, \bar{q}))$, producers $\Pi(s, q^M(\varphi(s), q_\mu, \bar{q}))$, and suppliers $G(s, q^M(\varphi(s), q_\mu, \bar{q}))$ over the set of standards S .*

The following result shows that technology adopters (distributors, producers, and suppliers) choose the efficient standard unanimously. The result shows that adopters choose the efficient standard whether or not inventors with SEPs participate in the SSO.

PROPOSITION 6. *For any number of inventors Y with SEPs, for any sizes H , I , J of the industry groups that adopt inventions, any number of standards T , any membership set $F \in \Lambda$ or $F = F_Y \cup F'$ where $F' \in \Lambda$, any decision rule δ , and for all values of the policy parameter μ , technology adopters unanimously choose the efficient standard $s^0 = s^*$.*

This result establishes that adopters unanimously choose the efficient standard even if there are SEPs. This shows that even though inventors obtain monopoly rents and capture all returns at the margin, adopters still prefer the efficient standard. If adopters outvote inventors, or at least outvote inventors who do not favor the efficient standard, then the SSO chooses the efficient standard. The next section considers voting by inventors.

The intuition for this result is as follows. If the industry capacity constraint is binding for all standards, adopters are indifferent across standards and marginal adopters are unaffected by the standard, so adopters are indifferent across standards and choose s^* . If the SSO output constraint is binding across standards, then again adopters are indifferent and choose s^* . If neither output constraint is binding across

standards, then more adopters have positive profits with the efficient standard than with other standards, so all adopters choose s^* . If the lower output constraint is binding for some standards but nonbinding for other standards, it follows that the constraint cannot be binding at the efficient standard. This holds because unrestricted output is increasing in the quality of the innovation. By increasing output in comparison to other standards, the efficient standard increases the number of adopters with positive profits, so all adopters choose s^* .

IV.2 The equilibrium standard with voting by inventors

Now consider how inventors vote on standards. In the absence of transfers among inventors, it is clear that inventors will vote only for those standards to which their SEPs apply. It is easy to construct examples that rule out inventors choosing the efficient standard. For example, suppose that there are three inventors and two standards, s' and s'' . Inventor 1 has SEPs only for standard s' and inventors 2 and 3 have SEPs only for standard s'' . Then, a majority of inventors always will choose the standard s'' , whether or not it is efficient.

To make sure that the efficient standard is attainable for a group consisting only of inventors, we can require that a majority of inventors own SEPs that apply to that standard, $\frac{N(s^*)}{Y} > \frac{1}{2}$. Then, it is possible for a majority of inventors to choose the efficient standard. This requirement would not rule out a majority of inventors having SEPs for other standards.

Inventors face an interesting trade-off between the level of total licensing revenues and the number of inventors sharing revenues. A more efficient standard could involve a greater number of owners than a less efficient standard. So, more owners can increase total revenues and yet lower the revenue per inventor. This has important effects on voting. For example, suppose that there are seven inventors and two standards, s' and s'' . The standards generate revenues $R' = 110$ and $R'' = 100$, so that standard s' is the efficient standard. Suppose further that three inventors have SEPs that cover only the standard s' , two inventors have SEPs that cover the standard s'' , and two inventors own SEPs that cover both standards. This

implies that the revenue per inventor for s' is 22 and the revenue per inventor for the standard s'' is 25. Then, three inventors will choose standard s' and four inventors will choose standard s'' . So, although a majority of inventors owns SEPs for the efficient standard, a majority of inventors will choose the inefficient standard s'' to obtain larger shares of lower revenues.

The example shows that inventors could choose the inefficient standard because of "defections" to the smaller group by two of the inventors that own SEPs applying to the efficient standard.¹⁷ This situation would be ruled out in general by the voting rule $\delta = \frac{N(s^*)}{Y}$ when a majority of inventors owns SEPs for the efficient standard.

Consider the choice of a technology standards by a group of inventors. The inventors play the voting game $g(\delta; F_Y)$.

PROPOSITION 7. *If $\frac{N(s^*)}{Y} > \frac{1}{2}$ and $\delta = \frac{N(s^*)}{Y}$, then for any number of standards T , for any number of inventors Y with SEPs, and for all values of the policy parameter μ , inventors choose s^* .*

This result is another aspect of the trade-off between voting power and market power. A larger group of inventors could have sufficient voting power to support a less efficient standard. However, a less efficient standard would offer lower average returns to those inventors that own SEPs that apply to the efficient standard.

The intuition for this result is that inventors with SEPs for both the efficient standard and a competing inferior standard will not join a larger group of inventors to support the inferior standard. The inferior standard generates lower total revenues and the larger size of the group will lower average revenues. So, each member of the group of inventors with SEPs applying to the efficient standard would obtain lower revenues by choosing an alternative standard. The voting rules blocks defections to smaller groups that would have higher average revenues with an inefficient standard.

Inventors' choice of the efficient standard is not affected by the value of the SSO policy parameter μ . The equilibrium monopoly royalty is $\rho^M(\varphi(s)) = \varphi(s) - \psi(q^M(\varphi(s), q_\mu, \bar{q}))$. If either the upper or the lower output constraint is binding,

¹⁷One way to rule out this situation is to assume that if $Y(s) \cap Y(s') \neq \emptyset$, then either $N(s) \leq \frac{N}{2}$ or $N(s) \geq N(s^*)$.

per-unit royalties vary exactly with the quality of the innovation, $\frac{d\rho^M(\varphi(s))}{d\varphi} = 1$. If neither of the output constraints is binding, per-unit royalties only partly reflects the effects of the standard,

$$\frac{d\rho^M(\varphi(s))}{d\varphi} = 1 - \psi'(q^M(\varphi(s), q_\mu, \bar{q})) \frac{d\widehat{q}^M(\varphi(s))}{d\varphi} \leq 1,$$

because $\psi(q)$ is increasing in q and $\widehat{q}^M(\varphi(s))$ is increasing in $\varphi(s)$. So, per-unit royalties and total royalties are nondecreasing in $\varphi(s)$. This implies that inventors will choose the efficient standard for any value of $\mu \in [0, 1]$.

Now consider a mixed standards organization that consists of both inventors and technology adopters. Because adopters unanimously prefer the efficient standard, but inventors prefer standards that depend on their inventions, there are incentives for as many adopters as possible to join the SSO.

Assume that all $H + I + J$ adopters and all Y inventors join the SSO. Assume further that adopters plus inventors with SEPs for s^* outnumber inventors without SEPs for s^* ,

$$H + I + J + N(s^*) \geq Y - N(s^*).$$

This rules out the possibility that the largest group in the SSO is a group of inventors having SEPs for an inefficient standard but not for the efficient standard.

There are two possibilities. Suppose first that $H + I + J \geq N(s^*)$. This rules out the possibility that some of the $N(s^*)$ inventors would defect to a smaller group of inventors to choose an inefficient standard because they would be outvoted by adopters. From the proof of Proposition 6, recall that none of the $N(s^*)$ inventors with SEPs for s^* would defect to a larger group of inventors because that would reduce average earnings. So, given these assumptions, the SSO would choose s^* by majority rule.

Alternatively, suppose that $H + I + J < N(s^*)$. In this situation, the SSO could apply a voting rule $\delta(s^*)$ equal to

$$\delta(s^*) = \frac{H + I + J + N(s^*)}{H + I + J + Y}. \quad (26)$$

This voting rule would block inventors with SEPs for s^* defecting to a smaller group $N(s)$ such that $H + I + J < N(s)$ for any $s \neq s^*$. It follows that with the voting rule $\delta(s^*)$, the SSO would choose s^* . From $H + I + J + N(s^*) \geq Y - N(s^*)$, note that $\delta(s^*) \geq 1/2$, so the SSO would at least require majority rule.

COROLLARY 1. *Let all adopters and inventors be members of the SSO and $H + I + J + N(s^*) \geq Y - N(s^*)$. Then, for any number of standards T , and for all values of the policy parameter μ , if either $H + I + J \geq N(s^*)$ and $\delta = 1/2$ or $H + I + J < N(s^*)$ and $\delta = \delta(s^*)$, the SSO chooses s^* .*

V Technology standards with disagreements among and within industry groups

The basic framework studied thus far demonstrates that market equilibrium prices are sufficient to align the interests of distributors, producers, and suppliers. The alignment of interests was observed both with market competition and with monopoly when inventors have SEPs. However, the market may not align interests as effectively when there are disagreements within industry groups about the effects of a standard.

To represent disagreements within the group of distributors, partition the set of standards S into two nonempty sets $\{S_A^I, S_B^I\}$. For standards s_A in S_A^I , preferences of distributors are represented as before, with low types receiving the greatest benefits,

$$u_i(s_A) = u(s_A) - \eta(i), \quad i \in [0, I]. \quad (27)$$

However, for standards s_B in S_B^I , the preferences of distributors are opposite those for standards in S_A^I , with high types receiving the greatest benefits,

$$u_i(s_B) = u(s_B) - \eta(I - i), \quad i \in [0, I]. \quad (28)$$

If the market equilibrium output is q , active distributors for standards in S_A^I are

$i \in [0, q]$ and active distributors for standards in S_B^I are $i \in [I - q, I]$.

Let the partition $\{S_A^H, S_B^H\}$ represent disagreements within the group of producers and let the partition $\{S_A^J, S_B^J\}$ represent disagreements within the group of suppliers. The partitions of the set of standards are different for the three industry groups. With disagreements within and among industry groups, the market equilibrium outputs and prices remain the same as in Section II. The welfare measures and other notation remain the same. So, the only effect of disagreements within industry groups is on voting for standards.

Proposition 8 shows that we can write the number of votes for the efficient standard as a function of the quality of the innovation, $H(\varphi(s^*))$, $I(\varphi(s^*))$, and $J(\varphi(s^*))$. This allows us to define a voting rule $\delta(\varphi(s^*); F)$ as a function of the quality of the innovation for any $F \in \Lambda$. The voting rule is the ratio of the votes for the efficient standard of each group that is in the SSO divided by the number of members of the SSO. For example, if all three groups are members of the SSO, the voting rule equals

$$\delta(\varphi(s^*); F_{H,I,J}) = \frac{H(\varphi(s^*)) + I(\varphi(s^*)) + J(\varphi(s^*))}{H + I + J}. \quad (29)$$

Proposition 8 shows that a majority of members of each group votes for the efficient standard and the number of votes for the efficient standard increases with the quality of the innovation.

PROPOSITION 8. *Without SEPs, for any sizes H, I, J of the industry groups, any number of standards T , any membership set $F \in \Lambda$, and disagreements within each industry group, technology adopters in the SSO choose the efficient standard $s^0 = s^*$ by majority rule, $\delta(\varphi(s^*); F) \geq \frac{1}{2}$. The number of votes for the efficient standard, $H(\varphi(s^*))$, $I(\varphi(s^*))$, and $J(\varphi(s^*))$, and the voting rule $\delta(\varphi(s^*); F)$ are non-decreasing in the quality of the innovation $\varphi(s^*)$.*

Because a majority of each group favors the efficient standard, it follows that a majority of members of an SSO composed of any set $F \in \Lambda$ also will favor the efficient standard. The proof is based on the fact that industry output is greater at the efficient standard than with other standards.

The intuition of the proof is as follows. Consider first the set of distributors. The

efficient standard is in one of the sets in the partition, say $s^* \in S_A$. Then, distributors will unanimously prefer s^* over other standards in S_A . Now compare the efficient standard with a standard in S_B . If active distributors for the two standards are distinct groups, and some distributors are inactive for both standards, the indifferent distributors vote for the efficient standard. Because the efficient standard increases output, a greater number of distributors are active under the efficient standard, and combined with the indifferent distributors, a majority of distributors vote for the efficient standard. Conversely, if active distributors for the two standards are not distinct groups, there must exist a distributor that is indifferent between the two standards. Because the efficient standard increases output, there must be a majority of distributors that prefers the efficient standard, $\frac{I(\varphi(s^*))}{I} \geq \frac{1}{2}$. The same result holds for producers and for suppliers.

The proof of Proposition 8 shows that a tie between two standards very rarely occurs within any group. Consider distributors for example. A tie requires several conditions to be satisfied simultaneously: the market is capacity constrained for the two standards, distributors are not in the scarce category of agents, and the groups of active distributors for the two standards overlap with each other. This implies that a tie cannot occur when all industry groups are included in the SSO.

Propositions 1 and 8 help explain why different standards organizations have different voting rules. Suppose that all three industry groups are members of the SSO. When there is agreement on ranking standards within all three industry groups, a near-consensus voting rule can be implemented, as shown by Proposition 1. When there are disagreements within all three groups, a majority voting rule can be implemented. The greater is the extent of the innovation, the more likely it is that the SSO can adopt a supra-majority voting rule because $\delta(\varphi(s^*); F)$ is nondecreasing in $\varphi(s^*)$.

In addition, when only one or two groups have disagreements, voting rules between the majority and near-consensus levels may be sufficient to achieve an efficient outcome. Suppose for example that distributors are the only group with internal disagreements, so $\frac{I(\varphi(s^*))}{I} \geq \frac{1}{2}$. Producers and suppliers choose the efficient standard unanimously by Proposition 1. So, an SSO composed of all three industry groups

chooses the efficient standard with a voting rule given by

$$\delta = \frac{H + I(\varphi(s^*)) + J}{H + I + J} \geq \frac{2H + I + 2J}{2(H + I + J)}.$$

If the three groups are about the same size, this implies that the voting rule is $\delta \geq 5/6$.

Consider now voting when there are SEPs and when there are disagreements within industry groups. We can write the number of votes for the efficient standard as a function of the quality of the innovation, $H^M(\varphi(s^*))$, $I^M(\varphi(s^*))$, and $J^M(\varphi(s^*))$. This allows us to define a voting rule $\delta^M(\varphi(s^*); F)$ for any $F \in \Lambda$ as a function of the quality of the innovation. The voting rule $\delta^M(\varphi(s^*); F)$ is the ratio of the votes for the efficient standard of each group in the SSO divided by the number of members of the SSO. For example, if all three groups are members of the SSO, the voting rule equals

$$\delta^M(\varphi(s^*); F_{H,I,J}) = \frac{H^M(\varphi(s^*)) + I^M(\varphi(s^*)) + J^M(\varphi(s^*))}{H + I + J}. \quad (30)$$

PROPOSITION 9. *For any number of inventors Y with SEPs, any sizes H, I, J of the industry groups, any number of standards T , any membership set $F \in \Lambda$, , and disagreements within each industry group, technology adopters in the SSO choose the efficient standard $s^0 = s^*$ by majority rule, $\delta^M(\varphi(s^*); F) \geq \frac{1}{2}$. The number of votes for the efficient standard, $H^M(\varphi(s^*))$, $I^M(\varphi(s^*))$, and $J^M(\varphi(s^*))$, and the voting rule $\delta^M(\varphi(s^*); F)$ are nondecreasing in the quality of the innovation $\varphi(s^*)$.*

The intuition for the proof of Proposition 9 is the same as that for Proposition 8. When inventors have SEPs, output is still increasing in the quality of the innovation. This implies that a majority of the members of any group will vote for the efficient standard. So, the more significant is the innovation $\varphi(s^*)$, the closer is the voting rule to a consensus.

Consider now a mixed standards organization that consists of inventors and all technology adopters. Suppose that adopters who favor the efficient standard outnumber inventors who do not have SEPs for the efficient standard, $H(\varphi(s^*)) + I(\varphi(s^*)) + J(\varphi(s^*)) \geq Y - N(s^*)$. Assume further that $H(\varphi(s^*)) + I(\varphi(s^*)) + J(\varphi(s^*)) \geq N(s^*)$.

Then, the SSO will choose the efficient standard s^* .

Alternatively, suppose that $H(\varphi(s^*)) + I(\varphi(s^*)) + J(\varphi(s^*)) \geq Y - N(s^*)$, but $H(\varphi(s^*)) + I(\varphi(s^*)) + J(\varphi(s^*)) < N(s^*)$. Suppose that the SSO adopts the voting rule

$$\delta(\varphi(s^*)) = \frac{H(\varphi(s^*)) + I(\varphi(s^*)) + J(\varphi(s^*)) + N(s^*)}{H + I + J + Y}.$$

As before, this rules out defection of inventors to a smaller group to increase average revenues. Suppose that a majority of inventors has SEPs for the efficient standard, $\frac{N(s^*)}{Y} > \frac{1}{2}$. Because a majority of adopters votes for the efficient standard, it follows that $\delta(\varphi(s^*)) > \frac{1}{2}$.

The main problem with disagreements within groups is that the market equilibrium need not provide ex post transfers that induce consensus. However, in this case it is also possible for alliances to form. In particular, agents that are high-cost under one standard and low-cost under another standard can form alliances with those agents that have the opposite situation. For example, distributors with opposite preferences across standards can form alliances. The alliances involves contractual transfers among members of the group, including mergers, acquisitions, industry consortia, technology sharing, and subcontracting production or distribution. Companies form alliances to develop technology and to sponsor standards in SSOs (Axelrod et al., 1995).

Alliances can form ex ante and determine transfers contingent on the outcome of standard setting. Such alliances would serve to align preferences and coordinate voting in the standards organization. So, alliances with transfers would allow the standards organization to implement near-consensus voting rules even with disagreements. So, the evolution of the industry and agreements among industry participants affect the formation and rules of SSOs.

Conversely, the rules of SSOs could affect market agreements within industry groups. Suppose that standards organizations choose consensus rules. Suppose also that diverse agents later enter the industry so that there are disagreements within industry groups. Then, the SSO rules may generate incentives for some agents to form alliances as means of addressing the voting requirements. Such alliances would

induce voting for efficient standards.

VI Discussion

Standards provide indicators of innovation because they represent combinations of many inventions and because new or revised standards reflect changes in technology. The efficiency of standards often cannot be observed directly so that theoretical analysis of standard setting becomes all the more necessary. This section applies standardization to define drastic innovations. The discussion considers some empirical implications of the analysis. Finally, the discussion briefly examines some public policy aspects of technology standards.

VI.1 Standards as indicators of innovation

We can interpret the SSO's policy constraint in terms of the extent of the innovation associated each standard. We can extend Arrow's (1962) terminology for individual inventions to the innovation represented by a standard s . The standards organization compares the innovation given by the efficient standard $\varphi(s^*)$ with the incremental effects $\varphi(\bar{s})$ of the benchmark standard \bar{s} . If the benchmark standard were to have no SEPs, this would place an upper limit on total per-unit royalties equal to the incremental contribution of the standard in comparison to the benchmark,

$$\bar{\rho}(s) = \varphi(s) - \varphi(\bar{s}). \quad (31)$$

Recall that the unconstrained monopoly royalty is $\hat{\rho}^M(\varphi(s)) = \varphi(s) - \psi(\hat{q}^M(\varphi(s)))$, where $\hat{q}^M(\varphi(s))$ is the unconstrained monopoly output. Define an innovation $\varphi(s)$ as a *drastic* innovation if the royalty constraint is nonbinding, $\hat{\rho}^M(\varphi(s)) \leq \bar{\rho}(s)$ and a *non-drastic* innovation if the royalty constraint is binding, $\hat{\rho}^M(\varphi(s)) > \bar{\rho}(s)$.

We now compare the SSO's choice between standards that have SEPs and those

that do not have SEPs.¹⁸

PROPOSITION 10. Suppose that there are two standards, the efficient standard s^* , for which there are SEPs, and the benchmark standard \bar{s} , for which are no SEPs. Then, if the innovation $\varphi(s^*)$ is drastic, technology adopters choose the efficient standard unanimously (or by majority rule if there are disagreements within groups) whether or not the SSO restricts royalties on SEPs. If the innovation $\varphi(s^*)$ is non-drastic, technology adopters choose the efficient standard unanimously (or by majority rule if there are disagreements within groups) if the SSO policy parameter is such that

$$\mu \geq \frac{\varphi(s^*) - \psi(\widehat{q}^M(\varphi(s^*))) - \varphi(\tilde{s})}{\varphi(\bar{s}) - \varphi(\tilde{s})}.$$

The result follows from the definition of the SSO's royalty limit, $\bar{\rho}(s, \mu) = \varphi(s) - \mu\varphi(\bar{s}) - (1 - \mu)\varphi(\tilde{s})$. The result finds that for drastic innovations, the presence of SEPs need not affect efficiency even if the technologies needed for the alternative standard are available without any licensing fees. The result suggests that we should observe efforts to regulate royalties when efficient innovations are non-drastic and have SEPs but alternative standards do not have SEPs. The tradeoff between the quality of the innovation and royalties only requires SSO regulation with non-drastic innovations.

Setting the policy parameter at $\mu = 1$ implies that $\bar{\rho}(s, 1) = \bar{\rho}(s)$. The tightest policy benchmark is equivalent to the greatest minimum output level, $q_1 = \widehat{q}(\varphi(\bar{s}))$.¹⁹ This implies that the innovation $\varphi(s)$ is *drastic* if the tightest minimum output constraint is nonbinding,

$$\widehat{q}^M(\varphi(s)) \geq q_1,$$

and the innovation $\varphi(s)$ is *non-drastic* if the tightest minimum output constraint is binding, $\widehat{q}^M(\varphi(s)) < q_1$. This implies that for drastic innovations, the lower output constraint $q \geq q_\mu$ is not binding for any μ . The policy parameter does not affect equilibrium royalties per unit of output. So, with drastic innovations, adopters and

¹⁸I am grateful to Dennis Carlton for a helpful discussion that suggested this comparison.

¹⁹Note that the lower output constraint is increasing in μ , $\frac{dq_\mu}{d\mu} = \widehat{q}'(\mu\varphi(\bar{s}) + (1 - \mu)\varphi(\tilde{s}))[\varphi(\bar{s}) - \varphi(\tilde{s})] > 0$.

inventors are not affected by an increase in the policy parameter μ .

Conversely, suppose that the innovation is non-drastic and the lower output constraint is binding. Then, adopters prefer increases in the policy parameter and inventor prefer reductions in the policy parameter. This is because an increase in the policy parameter μ would decrease royalties per unit of output, $\frac{d\rho(\varphi(s))}{d\mu} = -\psi'(q_\mu)\frac{dq_\mu}{d\mu} < 0$. Because the unconstrained output maximizes $R(\varphi(s), q)$, an increase in μ would decrease total licensing revenue for inventors. When the innovation is nondrastic and the lower output constraint is binding, agent profits are $\pi_h(s) = \theta(q_\mu) - \theta(h)$, $v_i(s) = \eta(q_\mu) - \eta(i)$, and $g_j(s) = \zeta(q_\mu) - \zeta(j)$. So, total distributor profits are increasing in μ ,

$$\frac{d}{d\mu} \int_0^{q_\mu} v_i(s) di = \eta'(q_\mu) q_\mu \frac{dq_\mu}{d\mu} > 0,$$

and similarly for producers and suppliers.

This discussion implies that tighter price regulation by the SSO increases social welfare if and only if the innovation represented by the efficient standard is non-drastic and the lower output constraint is binding at the efficient standard.

PROPOSITION 11. *Second-best social welfare is increasing in the SSO's policy parameter,*

$$\frac{dw^M(\varphi(s^*))}{d\mu} > 0,$$

if and only if $\widehat{q}^M(\varphi(s^)) < \widehat{q}(\mu\varphi(\bar{s}) + (1 - \mu)\varphi(\widetilde{s}))$.*

This effect is possible only if the efficient standard is a non-drastic innovation and inventors with SEPs for the efficient standard have sufficient market power. This may help explain variations in the IP rules of standards organizations, with SSOs in some industries focusing more on restricting *ex post* royalties as compared to other industries. When industries have incremental innovations, there may be a greater desire by distributors, producers, and suppliers to limit *ex post* royalties than when innovations are proceeding by leaps and bounds.

Proposition 10 also helps explain variation across industries in participation in standards organizations. In industries with incremental innovations, there is a greater

need for participation by many industry groups to counterbalance inventors. However, with sufficiently dynamic technological change, the standards organization can contain a greater proportion of inventors.

The result also suggests that the mission and the membership of standards organizations can change over time. In some industries, more significant technological changes occur in the early stages of industry development than in more mature stages. As a consequence, we may observe that in the early stages of industry development, inventors and early adopters dominate standards organizations. In later stages of industry development, greater numbers of distributors, producers, and suppliers participate in the standards organizations. Greater participation of technology adopters in the standards organizations over time is consistent with a desire to regulate licensing royalties as the pace of innovation diminishes.

The participation of inventors and early adopters in the initial stages of industry development also is likely to reflect the composition of the market. There are likely to be fewer distributors, producers and suppliers in the market in the early stages of industry development. Over time, innovation stimulates industry growth and more distributors, producers and suppliers enter the market and then begin to participate in standards organizations. This suggests that in the initial stages of industry growth, inventors and early adopters may battle over the *direction* of technological change. Licensing royalties will be less important because of the beneficial effects of drastic innovations. In the later stages of industry growth, the focus of standards organizations may shift to licensing royalties, reflecting the effects of both market composition and the *rate* of technological change.

VI.2 Empirical implications

There is a substantial empirical literature on standards organizations, including SSOs, standards development organizations (SDOs), industry consortia (Baron et al. 2014), alliances, and trade associations. Leiponen (2008) studies 3GPP and finds that industry associations and consortia facilitate the activities of SSOs; see also Rosenkopf and Tushman (1998). Firms form private alliances and consortia

to exchange information and coordinate their participation in SSOs; see Leiponen (2008) and Baron and Pohlman (2013). Spencer and Temple (2013) consider the contribution of technology standards to economic growth in the U.K..

The present analysis has a number of empirical implications. One set of implications is based on the significance of the quality of the innovation $\varphi(s)$ embodied in the standard s . The analysis shows that the greater is the innovation, the larger will be downstream output. This suggests that adoption of standards representing significant innovations or substantial revisions in standards should promote industry growth and reduce prices of products based on the standard. The analysis finds that greater innovations embodied in standards increase the profits of distributors, producers, or suppliers. In practice, adoption of significant standards and substantial revisions in standards may translate into growth of the industry. Such growth could take the form of expansion of existing firms or entry of new firms accompanied by creative destruction.

The analysis also suggests that when new industries form and drastic innovations occur, SSOs need not be as concerned with rules that regulate licensing revenues after standards are established. As the industry develops and incremental innovation are observed, SSOs will be more concerned with regulating licensing revenues. This further suggests that the SSO will reflect the interests of inventors and early adopters in the initial stages and will involve greater participation from distributors, producers and suppliers over time.

The analysis further suggests that more homogeneity within industry groups will be associated with consensus voting rules and less homogeneity will be associated with majority voting rules. Alternatively, the results of disagreements within industry groups may be the formation of multiple SSOs, and perhaps consolidation of SSOs as industry groups become more homogeneous. The discussion suggests that diversity of membership can help increase efficiency of standards, particularly when there are disagreements within industry groups.

It is difficult to evaluate directly whether or not technology standards are efficient in practice.²⁰ To determine whether a technology standard is efficient requires

²⁰The reason is analogous to the evaluating the efficiency predictions of neoclassical models of

consideration of alternative standards. However, alternative standards are not likely to be observable in practice because they were considered in SSO discussions rather than implemented in the market. Also, alternative standards are not observable in practice because the details of the standards were not fully developed and the technologies associated with those standards may be speculative.

Even if alternative standards could be observed, comparisons with the chosen standard may be impossible. There are many technologies associated with each alternative standard and those technologies could be highly complex, defying simple quality rankings. Technology standards also address interoperability of technologies, which can involve an extremely large number of potential interactions. The technologies embodied in standards often develop at the same time as the standards, and there is interaction between standard setting and invention (Spulber, 2013). Finally, the efficiency of technology standards ultimately depends on how they affect market outcomes. It is unlikely that the effects of standards on market outcomes can be directly observed, and certainly the effects of alternative standards that were not chosen by the SSO will not be observed.

This suggests that it would be useful to examine the efficiency of technology standards indirectly by considering the standard setting process itself. Baron and Spulber (2015) provide a data set that considers the membership and rules of SSOs and the development and revision of standards over time. Tsai and Wright (2015) consider SSO IP policies and find that changes over time are consistent with a competitive contracting process and diversity of technology adopters and contributors to the standard.

The question of whether or not standards are efficient also can be tested indirectly by studying the economic effects of standards. Rysman and Simcoe (2008) examine the efficiency of standards by considering patents disclosed to four major

competitive markets. Neoclassical analysis predicts that market equilibria will be Pareto optimal. In practice, it is usually not possible to directly observe how individuals rank market allocations, particularly in comparison to allocations that have not happened. However, it is possible to observe whether some of the predictions of market models are consistent with competitive market equilibria. For example, we observe some relationships between prices, outputs, and costs and we observe variations across markets and changes over time. This allows tests of the predictions of competitive market models.

SSOs (ANSI, IEEE, IETF, and ITU) and find that disclosure increases citations and shifts citations toward later years. Rysman and Simcoe (2008, p. 1932) find that SSOs "perform well in selecting important technologies" and, if patents citations indicate a causal relationship, their results suggest that SSO endorsements contribute to technology adoption.

The choice of efficient standards by SSOs suggests that companies will send engineers and other technical personnel as representatives to SSO meetings. This is in part because these specialized individuals can understand and contribute to the discussion of potential standards in highly technical committees that work on the details of technology standards. The present analysis also suggests that delegation to specialized technical representatives occurs because the focus of the discussions will be the choice of the best technologies. This could be examined empirically by observing what are the areas of expertise of company representatives at SSO meetings.

VI.3 Public policy implications

Antitrust authorities and other public policy makers are concerned that some industry groups will dominate standards organizations. Such industry groups could include distributors, producers, input suppliers, or inventors. The results presented here provide sufficient conditions under which voting on standards by SSOs selects the most efficient standard.

One concern is that SSOs will choose inefficient technology standards that confer market power on some industry groups, see Weiss and Sirbu (1990), Axelrod et al. (1995), Teece and Sherry (2003), Schmalensee (2009), and Lerner and Tirole (2015). Teece and Sherry (2003) argue that SSOs could choose inefficient technology standards because: adopters seek to avoid royalties, SSO rules favor adopters over inventors, and engineers making decisions are biased against technologies protected by IP. Conversely, others argue that technology standards will be inefficient because owners of SEPs seek those standards that increase their patent licensing revenues. Simcoe et al. (2009) discuss market power effects of standards, suggesting that smaller firms that own IP face a trade-off between opening a standard to encour-

age technology adoption and closing a standard to create monopoly rents, whereas larger firms with market power downstream favor greater competition upstream in technology markets. They find that entrepreneurs rely on compatibility standards to supply components to the industry.

The present analysis suggests that even with SEPs, technology adopters will choose efficient standards. Even if inventors with SEPs extract monopoly rents, adopters are either better off or indifferent in comparison with other standards. The same reasoning applies if royalties are constrained by low-cost alternative technologies or by royalty constraints imposed by SSO rules.

A related policy concern is that if some industry group dominates the standards organization, it will seek standards that give them a competitive advantage in the marketplace. Then, technology standards would distort outputs and prices in favor of distributors, producers, or input suppliers. One concern is that industry members will use cooperative agreements to raise prices, thereby reducing economic welfare, see FTC and U.S. DOJ (2000) and FTC (2011, p. 192). Bar and Leiponen (2014) find that standards affect competition in communication and information technology (CIT) industries. Schmidt (2014) considers the complementarity of SEPs and compares the effects of vertical and horizontal integration. In Lerner and Tirole (2015), inventors with SEPs choose licensing royalties non-cooperatively as in the Cournot complementary monopolies setting, so that total royalties exceed the monopoly level. In their setting, technology standards increase the prices of licenses of SEPs and distort the market equilibrium after standards are established.

Standards organizations have different policies and rules regarding the disclosure of IP by their members and licensing of IP after standards are chosen. Some SSOs require owners of SEPs to license their technologies on terms that are Fair, Reasonable, and Non-Discriminatory (FRAND), see Geradin and Rato (2007), Epstein and Kappos (2013), and Sidak (2013, 2015).

The present analysis finds that industry members may be concerned with incremental inventions that generate monopoly rents and may seek commitments to lower royalties. If the efficient standard represents a drastic innovation, it generates monopoly royalties that are not limited by the tightest royalty constraint. With drastic

innovation, the welfare gains from technological improvements outweigh the effects of higher royalties. The efficient technology generates an innovation that increases the profits of adopters.

In the present setting monopoly rents for inventors represents a worst case scenario. In practice, there often are competitive alternatives for the inventions that satisfy the standard. Also, there may be multiple substitute inventions because inventors simply declare their inventions to be SEPs, even though adopters can satisfy the standard with alternative inventions. In addition, continual technological change makes technologies obsolete, reducing or eliminating royalties for SEPs. Also, in practice, there are competing standards and competing SSOs. Adopters also have complementary assets that are necessary to implement innovations and further limit the returns to inventors with SEPs. Spulber (2013) discusses some implications of the interaction between technology standards, market conduct, and economic performance.

The analysis considers the efficiency of standards for a given organization that contains subsets of members of an industry. Many industries have multiple standards organizations, with entry and exit of organizations in response to changes in technology and market conditions. Standards organization may compete with each other to provide standardization services to their members, so there may be excessive or insufficient standardization. This raises the question of whether standards organizations are efficient in terms of the numbers of participants and the numbers of organizations within an industry. To answer this question requires consideration of how the formation of cooperative standards organizations interacts with market competition among members of the industry.

Propositions 8 and 9 raise questions about industry participation. For example, given the partition $\{S_A^H, S_B^H\}$, low- h types of producers prefer standards in S_A^H , which includes the efficient standard, and high- h types of producers prefer standards in the set S_B^H . Then, systematic exclusion of a subset of producers, say for example high h types of producers, could result in the choice of an inefficient standard. This might occur if high- h producers favoring standards in S_B^H dominate the membership of an SSO. Then, even though distributors and input suppliers prefer the efficient standard,

the SSO could choose an inefficient standard.

Such biases in membership could occur in an international organization in which industry groups from some countries participate more than industry groups from other countries.²¹ In a similar way, if there are disagreements between incumbent firms or new entrants within an industry group, the resulting standard might be inefficient depending on which subgroup participates more in the SSO. This suggests that SSOs should be as inclusive as possible both within an economy and across economies.

The present analysis shows that technology standards satisfy static efficiency for a given set of potential technologies. Technology standards affect dynamic efficiency because they affect incentives for invention and innovation. Companies invent in anticipation of technology standards and technology standards depend on invention, so standard setting and invention are interconnected (Spulber, 2013). Additional research is needed to examine whether the choice of technology standards by SSOs generates efficient investment in invention and innovation.

VII Conclusion

The combination of voting on standards and market competition generates efficient standard setting. The choice of technology standards by SSOs depends on interactions between voting power and market power. In a competitive market, the long side of the market has greater voting power but competes away economic rents at the margin, and the opposite is the case for the short side of the market. The countervailing effects of the size of groups of economic agents in cooperative organizations and competitive markets generate efficient standards.

In a competitive market, the analysis suggests that standards can be invariant to changes in industry structure. This means that standards will tend to be stable even with entry, exit, entrepreneurship, mergers, and acquisitions. The transaction costs of industry coordination and the costs of revising or replacing standards

²¹See Delimatsis (2015) on international aspects of technology standards.

should further reinforce stability in standards. In addition, the organizational costs of implementing new standards in new products and production processes will tend to promote stability of standards. These forces help explain the stability of standards during periods of significant change in industry structure. Although standards are steadily revised and replaced with new generations, these changes may be less frequent than changes in market conditions.

The discussion helps explain the variation of voting rules among SSOs, ranging from majority rule to consensus requirements. When the main disagreements are among industry groups and there are no SEPs, SSO members unanimously prefer technology standards. This is because *ex post* transfers in competitive markets are sufficient to generate efficient standards. When there are disagreements both within and among industry groups, a majority of SSO members prefer efficient standards. This is because there are more active market participants with the efficient standard than with other standards, so that a majority of industry members prefer the efficient standard. Even when there are disagreements within groups of adopters, the more significant the innovation, the more the voting rule approaches a consensus

In the extreme case in which inventors capture monopoly rents, SSOs still choose the efficient standard. Inventors obtain monopoly rents when they choose license offers non-cooperatively. This has important implications for voting by inventors and adopters. When inventors share monopoly rents, they have incentives to avoid larger coalitions that support inefficient standards. Although inventors may have incentives to join smaller coalitions to support inefficient standards, voting rules can limit this outcome. In addition, the participation of adopters in SSOs tends to reduce the effects of inventors on SSO decisions. When standards generate incremental inventions, voting by adopters in SSOs and voting rules help achieve efficient standards. When standards generate drastic innovations, there is no need to restrict *ex post* royalties because the efficient standard increases net benefits.

Industry growth and development often involve both entry of technology adopters in the market and broadening participation of industry members in SSOs. In this way, greater competition in the market accompanies increased interaction within cooperative standards organizations. Technology standards will be efficient when

SSO decision making reflects the countervailing effects of voting power and market power.

VIII Appendix

PROOF OF PROPOSITION 1. Suppose first that market equilibria are not capacity constrained for any $s \in S$. Then, the marginal producer, distributor, and supplier have zero profits for all $s \in S$ and are indifferent. Inframarginal producers have profits $\pi_h(s) = \theta(\widehat{q}(\varphi(s))) - \theta(h)$. Inframarginal distributors have profits $v_i(s) = \eta(\widehat{q}(\varphi(s))) - \eta(i)$. Inframarginal suppliers have profits $g_j(s) = \zeta(\widehat{q}(\varphi(s))) - \zeta(j)$. Because $\theta(h)$, $\eta(i)$, and $\zeta(j)$ are increasing and $\widehat{q}(\varphi(s))$ is increasing in $\varphi(s)$, all inframarginal agents prefer s^* to all other $s \in S$ and so choose s^* .

Next suppose that market equilibria are capacity constrained for all $s \in S$. (i) Let distributors be in the scarce category, $\bar{q} = I < \min\{H, J\}$. All distributors have positive profits $v_i(s) = \varphi(s) - \psi(\bar{q}) + \eta(I) - \eta(i)$ and so strictly prefer s^* to all other $s \in S$. Producers have profits $\pi_h(s) = \theta(\bar{q}) - \theta(h)$ and are indifferent across standards. Suppliers have profits $g_j(s) = \zeta(\bar{q}) - \zeta(j)$ and are indifferent across standards. So, all agents choose s^* . (ii) Let producers be in the scarce category, $\bar{q} = H < \min\{I, J\}$. Producers have positive profits $\pi_h(s) = \varphi(s) - \psi(\bar{q}) + \theta(\bar{q}) - \theta(h)$. distributors and suppliers are indifferent across standards. So, all agents choose s^* . (iii) Let suppliers be in the scarce category, $\bar{q} = J < \min\{H, I\}$. Suppliers have positive profits $g_j(s) = \varphi(s) - \psi(\bar{q}) + \zeta(\bar{q}) - \zeta(j)$. Producers and distributors are indifferent across standards. So, all agents choose s^* .

Finally, suppose that market equilibria are capacity constrained for all $s \in \bar{S}$ and not capacity constrained for $s \in \widehat{S}$, where $\bar{S} \cup \widehat{S} = S$ and $\bar{S} \cap \widehat{S} = \emptyset$. Then, because $\widehat{q}(\varphi(s))$ is increasing in $\varphi(s)$ it follows that $s^* \in \bar{S}$. So, if restricted to standards in \bar{S} , all agents would choose s^* , as already shown. Now, choose any standard $s' \in \widehat{S}$. Then, given s' , the marginal producer, distributor, and supplier have zero profits.

Note that $\varphi(s^*) > \varphi(s')$ and

$$q^*(\varphi(s'), \bar{q}) = \widehat{q}(\varphi(s')) < \bar{q} = q^*(\varphi(s^*), \bar{q}).$$

This implies that $v_i(s') < 0 \leq v_i(s^*)$, $\pi_h(s') < 0 \leq \pi_h(s^*)$, and $g_j(s') < 0 \leq g_j(s^*)$ for all agents with types h, i or j in the set $(\widehat{q}(\varphi(s')), \bar{q}]$, so those agents prefer s^* to s' . Agents with types h, i or j greater than \bar{q} are indifferent and choose s^* . Consider agents with types h, i or j less than $\widehat{q}(\varphi(s'))$. Consider first $\bar{q} = I < \min\{H, J\}$, so that the market equilibrium is of type (i). Because $\bar{q} = q^*(\varphi(s^*), \bar{q})$ it follows that $\widehat{q}(\varphi(s^*)) \geq \bar{q}$ and so $\varphi(s^*) = \psi(\widehat{q}(\varphi(s^*))) \geq \psi(\bar{q})$. For distributors with type i less than $\widehat{q}(\varphi(s'))$, this implies

$$v_i(s^*) = \varphi(s^*) - \psi(\bar{q}) + \eta(I) - \eta(i).$$

It follows that $v_i(s^*) > \eta(I) - \eta(i)$. Also, because $\widehat{q}(\varphi(s')) < \bar{q} = I$, we have

$$\eta(I) - \eta(i) > \eta(\widehat{q}(\varphi(s'))) - \eta(i) = v_i(s').$$

So, $v_i(s^*) > v_i(s')$ for all i less than $\widehat{q}(\varphi(s'))$, so those distributors choose s^* . For producers with type h less than $\widehat{q}(\varphi(s'))$, profits with standard s' equal $\pi_h(s') = \theta(\widehat{q}(\varphi(s'))) - \theta(h)$ and profits with standard s^* equal $\pi_h(s^*) = \theta(\bar{q}) - \theta(h)$. So, $\widehat{q}(\varphi(s')) < \bar{q}$ implies that $\pi_h(s^*) > \pi_h(s')$, so those producers choose s^* . For suppliers with type j less than $\widehat{q}(\varphi(s'))$, profits with standard s' equal $g_j(s') = \zeta(\widehat{q}(\varphi(s'))) - \zeta(j)$ and profits with standard s^* equal $g_j(s^*) = \zeta(\bar{q}) - \zeta(j)$. So, $\widehat{q}(\varphi(s')) < \bar{q}$ implies that $g_j(s^*) > g_j(s')$, so those suppliers choose s^* . So, all distributors, producers, and buyers choose $s^* \in S$. The same analysis applies for market equilibrium (ii), $\bar{q} = H < \min\{I, J\}$, and for market equilibrium (iii), $\bar{q} = J < \min\{H, I\}$. So, agents unanimously choose s^* .

Suppose now that the members of the standards organization include any two groups or only one group. Then, by unanimity, it follows that the members of the standards organization unanimously choose s^* for all $F \in \Lambda$. Also by unanimity, the result holds for any decision rule δ . \square

PROOF OF PROPOSITION 2. Because $\varphi(s^*) > \varphi(s)$, we have $q^*(\varphi(s^*), \bar{q}) \geq q^*(\varphi(s), \bar{q})$. This also implies that the equilibrium standard maximizes distributor profits,

$$\int_0^{q^*(\varphi(s^*), \bar{q})} v_i(s^*) di \geq \int_0^{q^*(\varphi(s), \bar{q})} v_i(s^*) di \geq \int_0^{q^*(\varphi(s), \bar{q})} v_i(s) di.$$

The same holds for producers and suppliers. \square

EQUAL NUMBER OF MEMBERS OF INDUSTRY GROUPS. The results in Propositions 1 and 2 hold if two or more groups have the same number of members. For example, suppose that all three groups have the same total numbers, $H = I = J = \bar{q}$. Let the bargaining power of distributors α , producers β , and suppliers γ take values in the unit interval and $\alpha + \beta + \gamma = 1$. If the capacity constraint is binding, market equilibrium prices divide rents at the margin.²² Then, prices depend on the relative bargaining power of the economic agents,

$$p(s) = (1 - \alpha)u_{\bar{q}}(s) + \alpha[c_{\bar{q}}(s) + k_{\bar{q}}(s)].$$

The market equilibrium input price is

$$r(s) = (1 - \gamma)k_{\bar{q}}(s) + \gamma[u_{\bar{q}}(s) - c_{\bar{q}}(s)].$$

Similar prices result if any two industry groups have the same number of members. If the two groups of equal size are smaller than the third group, the two smaller groups divide marginal rents and the larger group does not obtain marginal rents. If the two groups of equal size are larger than the other group, the smaller group obtains marginal rents.

These prices give expressions for profits, $\psi_j(s) = \gamma[\varphi(s) - \psi(\bar{q})] + \zeta(\bar{q}) - \zeta(j)$, $\pi_h(s) = \beta[\varphi(s) - \psi(\bar{q})] + \theta(\bar{q}) - \theta(h)$, and $v_i(s) = \eta(\bar{q}) - \eta(i) + \alpha[\varphi(s) - \psi(\bar{q})]$. Notice that the expressions for profits depend on the incremental effects of the standard. It

²²With equal numbers of agents in two or more groups, the market equilibrium with bargaining over rents at the margin is related to Bohm-Bawerk's (1891) method of marginal pairs. In his framework, the marginal agents determine the market-clearing price and quantity, that is, the buyer-seller pair who have the smallest positive difference between the buyer's value and that of the seller, or by the marginal pair who are excluded from trade.

follows immediately that agents unanimously choose the efficient standard.

PROOF OF PROPOSITION 3. For a given standard s , an inventor y has profits $\xi_y(s, q) = \frac{R(\varphi(s), q)\lambda_s(y)}{N(s)}$. So, an inventor with SEPs for the standard chooses the licensing offer x_y to maximize total revenues $R(\varphi(s), q)$. The inventor does not gain anything from choosing a maximum license offer greater than the competitive equilibrium, so we can restrict attention to maximum license offers that are less than or equal to the competitive equilibrium, $x_y \leq q^*(\varphi(s), \bar{q})$. This implies that the total demand for licenses equals the minimum of the maximum license offers,

$$q = \min\{x_y; y \in Y(s)\}.$$

So, each inventor $y \in Y(s)$ chooses the license schedule $X_y(q_y)$ to maximize $R(\varphi(s), q)$ subject to $q = \min\{x_{\tilde{y}}; \tilde{y} \in Y(s)\}$ and $q_\mu \leq q \leq \bar{q}$. If $x_{-y} > q^M(\varphi(s), q_\mu, \bar{q})$, the inventor strictly prefers $x_y = q^M(\varphi(s), q_\mu, \bar{q})$. If $x_{-y} \leq q^M(\varphi(s), q_\mu, \bar{q})$, the inventor is indifferent between all $x_y \geq x_{-y}$ and strictly prefers any $x_y \geq x_{-y}$ to any $x_y < x_{-y}$. So, $x_y^0 = q^M(\varphi(s), q_\mu, \bar{q})$ is the unique weakly dominant strategy for inventor y . This holds for all $y \in Y(s)$. If there are multiple profit-maximizing monopoly outputs, it can be shown that the unique weakly dominant strategy equilibrium is the smallest profit-maximizing monopoly output. \square

PROOF OF PROPOSITION 4. Inventors choose $q^M(\varphi(s), q_\mu, \bar{q}) = \hat{q}^M(\varphi(s))$ if the constraints are non-binding. By standard monotone comparative statics arguments, the highest profit-maximizing monopoly output $\hat{q}^M(\varphi(s))$ is increasing in the quality of the innovation because output and the quality of the innovation are complements, $\frac{\partial^2 R(\varphi(s), q)}{\partial q \partial \varphi(s)} = 1$. The highest monopoly output is continuous because $\psi(q)$ is twice differentiable. The unconstrained monopoly output is less than the competitive output, $\hat{q}^M(\varphi(s)) < \hat{q}(\varphi(s))$. The profit-maximizing output is $q^M(\varphi(s), q_\mu, \bar{q}) = q_\mu$ for sufficiently low $\varphi(s)$ and $q^M(\varphi(s), q_\mu, \bar{q}) = \bar{q}$ for sufficiently high $\varphi(s)$.

Because $\varphi(s^*) > \varphi(s)$ for all $s \in S - s^*$, it follows that $\hat{q}^M(\varphi(s^*)) > \hat{q}^M(\varphi(s))$. So, if the upper and lower constraints are not binding at $\varphi(s^*)$, monopoly output is maximized at $\varphi(s^*)$. If the upper-constraint is binding at $\varphi(s^*)$, $q^M(\varphi(s^*), q_\mu, \bar{q}) = \bar{q}$ is the maximum output. If the lower-constraint is binding at $\varphi(s^*)$, it is also binding

for all $\varphi(s)$ so that $q^M(\varphi(s^*), q_\mu, \bar{q}) = q_\mu$ is the maximum output. So, if s^* maximizes $\varphi(s)$ it also maximizes $q^M(\varphi(s), q_\mu, \bar{q})$.

Given the monopoly output level, we can write social welfare as a function of the incremental effects of the standard,

$$w^M(\varphi(s)) = \varphi(s)q^M(\varphi(s), q_\mu, \bar{q}) - \int_0^{q^M(\varphi(s), q_\mu, \bar{q})} \psi(x)dx.$$

The marginal effects of the standard on second-best welfare equal

$$\frac{dw^M(\varphi(s))}{d\varphi(s)} = q^M(\varphi(s), q_\mu, \bar{q}) + [\varphi(s) - \psi(q^M(\varphi(s), q_\mu, \bar{q}))] \frac{dq^M(\varphi(s), q_\mu, \bar{q})}{d\varphi(s)}.$$

From the monopolist's maximization problem, it follows that $\varphi(s) - \psi(q^M(\varphi(s), q_\mu, \bar{q})) > 0$ and $\frac{dq^M(\varphi(s), q_\mu, \bar{q})}{d\varphi(s)} \geq 0$. It follows that $\frac{dw^M(\varphi(s))}{d\varphi(s)} > 0$ so if s^* maximizes $\varphi(s)$ it also maximizes $w^M(\varphi(s))$. Because $\varphi(s^*) > \varphi(s)$ for all $s \in S - s^*$, it follows that $w^M(\varphi(s^*)) > w^M(\varphi(s))$ for all $s \in S - s^*$, so s^* is the unique standard that maximizes $w^M(\varphi(s))$.

By the envelope theorem, the marginal effects of the standard on monopoly profit equals

$$\frac{dR^M(\varphi(s))}{d\varphi(s)} = q^M(\varphi(s), q_\mu, \bar{q}) > 0.$$

so if s^* maximizes $\varphi(s)$ it also maximizes $R^M(\varphi(s))$. Because $\varphi(s^*) > \varphi(s)$ for all $s \in S - s^*$, it follows that $R^M(\varphi(s^*)) > R^M(\varphi(s))$ for all $s \in S - s^*$, so s^* is the unique standard that maximizes $R^M(\varphi(s))$. \square

PROOF OF PROPOSITION 5. Because $\varphi(s^*) > \varphi(s)$, we have $q^M(\varphi(s^*), q_\mu, \bar{q}) \geq q^M(\varphi(s), q_\mu, \bar{q})$. This also implies that the equilibrium standard maximizes distributor profits,

$$\int_0^{q^M(\varphi(s^*), q_\mu, \bar{q})} v_i(s^*) di \geq \int_0^{q^M(\varphi(s), q_\mu, \bar{q})} v_i(s^*) di \geq \int_0^{q^M(\varphi(s), q_\mu, \bar{q})} v_i(s) di.$$

The same holds for producers and suppliers. \square

PROOF OF PROPOSITION 6. Partition the set of standards S into three sets,

$S_{\bar{q}}$, $S_{\hat{q}}$, and S_{q_μ} . The upper constraint on output is binding for all $s \in S_{\bar{q}}$. Neither of the constraints on output is binding for all $s \in S_{\hat{q}}$. The lower constraint on output is binding for all $s \in S_{q_\mu}$. Recall that $\rho(\varphi(s)) = \varphi(s) - \psi(q^M(\varphi(s), q_\mu, \bar{q}))$.

Suppose first that $S_{\bar{q}} = S$, so the marginal agents are given by \bar{q} . Marginal and supramarginal agents have zero profits and are indifferent across all $s \in S_{\bar{q}}$. Inframarginal agents have profits $\pi_h(s) = \theta(\bar{q}) - \theta(h)$, $v_i(s) = \eta(\bar{q}) - \eta(i)$, and $g_j(s) = \zeta(\bar{q}) - \zeta(j)$. So, all inframarginal agents are indifferent. So, all agents choose s^* . Next, suppose that $S_{q_\mu} = S$, so the marginal agents are given by q_μ . Inframarginal agents have profits $\pi_h(s) = \theta(q_\mu) - \theta(h)$, $v_i(s) = \eta(q_\mu) - \eta(i)$, and $g_j(s) = \zeta(q_\mu) - \zeta(j)$. By the same reasoning, all agents choose s^* .

Now suppose that $S_{\hat{q}} = S$, so the marginal agents are given by $\hat{q}^M(\varphi(s))$. Marginal and supramarginal agents have zero profits and inframarginal agents have profits $\pi_h(s) = \theta(\bar{q}) - \theta(h)$, $v_i(s) = \eta(\bar{q}) - \eta(i)$, and $g_j(s) = \zeta(\bar{q}) - \zeta(j)$. Agents that are marginal, inframarginal, or supramarginal for all $s \in S_{\hat{q}}$ are indifferent and choose s^* . Next, consider the group of agents that are inframarginal for some s but marginal or supramarginal for other s . Because $\hat{q}^M(\varphi(s))$ is increasing in $\varphi(s)$, the greatest number of those agents are inframarginal at s^* , and therefore strictly prefer s^* . So, all agents choose s^* .

If the set of standards such that industry capacity is binding is empty, $S_{\bar{q}} = \emptyset$, but not the other two sets, $S_{q_\mu} \neq \emptyset$, and $S_{\hat{q}} \neq \emptyset$, it must be the case that $s^* \in S_{\hat{q}}$. All agents choose s^* among standards in $S_{\hat{q}}$, as already shown. Now compare s^* with any $s \in S_{q_\mu}$. Agents that are inframarginal for both or supramarginal for standards, are indifferent and choose s^* . Because $\hat{q}^M(\varphi(s))$ is increasing in $\varphi(s)$ and $\hat{q}^M(\varphi(s^*)) > q_\mu$, the group of agents that are inframarginal for s^* but marginal or supramarginal for $s \in S_{q_\mu}$ strictly prefer s^* . So, all agents choose s^* . Conversely, if $S_{\bar{q}} \neq \emptyset$, then whatever is the case for the other two sets, it must be the case that $s^* \in S_{\bar{q}}$. By the same reasoning, all agents choose s^* . So, the standards organization always chooses s^* . \square

PROOF OF PROPOSITION 7. If $Y(s) \cap Y(s^*) = \emptyset$ for $s \neq s^*$, then $N(s) \leq Y - N(s^*) < N(s^*)$, so inventors in $Y(s^*)$ have more votes than those in $Y(s)$. Consider now $s \neq s^*$ such that $Y(s) \cap Y(s^*) \neq \emptyset$. If $N(s) < N(s^*)$, inventors in

$Y(s)$ cannot choose s because $\delta = \frac{N(s^*)}{Y}$. Suppose now that $N(s) \geq N(s^*)$. Because $R^M(\varphi(s^*)) > R^M(\varphi(s))$ and $N(s) \geq N(s^*)$, for any inventor $y \in Y(s) \cap Y(s^*)$,

$$\xi_y(s^*) = R^M(\varphi(s^*)) \frac{1}{N(s^*)} > R^M(\varphi(s)) \frac{1}{N(s)} = \xi_y(s).$$

This implies that all members of $Y(s^*)$ will choose s^* , which satisfies the voting rule $\delta = \frac{N(s^*)}{Y}$. So, given this voting rule, inventors choose s^* . \square

PROOF OF PROPOSITION 8. The proof focuses on distributors, and the same arguments apply for producers and suppliers. For ease of notation, drop the superscripts in the partition $\{S_A^I, S_B^I\}$, maintaining the assumption that the three sets of partitions differ across the industry groups. Suppose without loss of generality that the efficient standard s^* is in the set S_A for distributors. Also, for ease of notation, let $s_A = s^*$ and let s_B be any standard in S_B . It follows that $\varphi(s_A) > \varphi(s_B)$ and $q^*(\varphi(s_A), \bar{q}) \geq q^*(\varphi(s_B), \bar{q})$. Suppose first that $q^*(\varphi(s_A), \bar{q}) < I - q^*(\varphi(s_B), \bar{q})$, so there is no overlap between active distributors under the two standards so that distributors in the set $(q^*(\varphi(s_A), \bar{q}), I - q^*(\varphi(s_B), \bar{q}))$ are inactive and indifferent and vote for s_A . Also, distributors in $[0, q^*(\varphi(s_A), \bar{q})]$ vote for s_A and distributors in $[I - q^*(\varphi(s_B), \bar{q}), I]$ vote for s_B . So, there are $I - q^*(\varphi(s_B), \bar{q})$ votes for s_A and $q^*(\varphi(s_B), \bar{q})$ votes for s_B . A majority choose s_A because

$$I - q^*(\varphi(s_B), \bar{q}) > q^*(\varphi(s_A), \bar{q}) \geq q^*(\varphi(s_B), \bar{q}).$$

Because output depends on $\varphi(s^*)$, the number of votes for s^* , $I(\varphi(s^*))$, also is a function of $\varphi(s^*)$. It follows that $\frac{I(\varphi(s^*))}{I} > \frac{1}{2}$.

Suppose next that there is an overlap between the sets of active agents under the two standards, $q^*(\varphi(s_A), \bar{q}) \geq I - q^*(\varphi(s_B), \bar{q})$. Consider market equilibria that are not capacity constrained for s_A and s_B . Then, the marginal and supramarginal distributors have zero profits both standards. For standard s_A , active distributors are $i \in [0, \widehat{q}(\varphi(s_A))]$ and have profits

$$v_i(s_A) = \eta(\widehat{q}(\varphi(s_A))) - \eta(i).$$

For standard s_B , active distributors are $i \in [I - \widehat{q}(\varphi(s_B)), I]$ and have profits

$$v_i(s_B) = \eta(\widehat{q}(\varphi(s_B))) - \eta(I - i).$$

It follows that the indifferent distributor i^* is given by

$$\eta(\widehat{q}(\varphi(s_A))) - \eta(i^*) = \eta(\widehat{q}(\varphi(s_B))) - \eta(I - i^*).$$

Rearranging terms implies that

$$\eta(i^*) - \eta(I - i^*) = \eta(\widehat{q}(\varphi(s_A))) - \eta(\widehat{q}(\varphi(s_B))).$$

Because $\eta(\cdot)$ and $\widehat{q}(\varphi)$ are increasing functions, $\eta(\widehat{q}(\varphi(s_A))) > \eta(\widehat{q}(\varphi(s_B)))$ so that $\eta(i^*) > \eta(I - i^*)$. This implies that $i^* > I - i^*$ so $\frac{I(\varphi(s^*))}{I} > \frac{1}{2}$.

Next suppose that market equilibria are capacity constrained for s_A and s_B . Let distributors be in the scarce category, $\bar{q} = I < \min\{H, J\}$, so that all distributors are active with either standard and have positive profits,

$$v_i(s_A) = \varphi(s_A) - \psi(\bar{q}) + \eta(\bar{q}) - \eta(i),$$

$$v_i(s_B) = \varphi(s_B) - \psi(\bar{q}) + \eta(\bar{q}) - \eta(I - i).$$

It follows that the indifferent distributor i^* is given by

$$\eta(i^*) - \eta(I - i^*) = \varphi(s_A) - \varphi(s_B).$$

Because $\varphi(s_A) > \varphi(s_B)$, it follows that $i^* > I - i^*$ so $\frac{I(\varphi(s^*))}{I} > \frac{1}{2}$.

Maintaining the hypothesis that market equilibria are capacity constrained for all $s \in S$, either let producers be in the scarce category, $\bar{q} = H < \min\{I, J\}$, or let suppliers be in the scarce category, $\bar{q} = J < \min\{H, I\}$ and $\bar{q} \geq I - \bar{q}$, so there is an overlap. Active distributors have profits

$$v_i(s_A) = \eta(\bar{q}) - \eta(i),$$

$$v_i(s_B) = \eta(\bar{q}) - \eta(I - i).$$

So, the indifferent distributor is $i^* = 1/2$ and $\frac{I(\varphi(s^*))}{I} = \frac{1}{2}$.

Now let the market equilibrium be capacity constrained for s_A but not for s_B , that is, $\widehat{q}(\varphi(s_B)) \leq \bar{q} < \widehat{q}(\varphi(s_A))$. Let $\bar{q} = I < \min\{H, J\}$. Given the overlap, $I - \widehat{q}(\varphi(s_B)) \leq \bar{q}$, the indifferent distributor is defined by

$$\eta(i^*) - \eta(I - i^*) = \varphi(s_A) - \psi(\bar{q}) + \eta(\bar{q}) - \eta(\widehat{q}(\varphi(s_B))) > 0,$$

Because $\bar{q} \geq \widehat{q}(\varphi(s_B))$ and $\varphi(s_A) > \psi(\bar{q})$, it follows that $i^* > I - i^*$ so $\frac{I(\varphi(s^*))}{I} > \frac{1}{2}$. Next, let $\bar{q} = H < \min\{I, J\}$ or $\bar{q} = J < \min\{H, I\}$. Then, $v_i(s_A) = \eta(\bar{q}) - \eta(i)$ and $v_i(s_B) = \eta(\widehat{q}(\varphi(s_B))) - \eta(I - i)$ so that

$$\eta(i^*) - \eta(I - i^*) = \eta(\bar{q}) - \eta(\widehat{q}(\varphi(s_B))) > 0.$$

Again, $\bar{q} \geq \widehat{q}(\varphi(s_B))$ implies that $i^* > I - i^*$ so $\frac{I(\varphi(s^*))}{I} > \frac{1}{2}$. Finally, notice that because output is nondecreasing in $\varphi(s)$, it is not possible for the market equilibrium to be capacity constrained for s_B but not for s_A . This implies that $\frac{I(\varphi(s^*))}{I} \geq \frac{1}{2}$. The same result holds for producers and suppliers, regardless of the partition. Therefore, the result holds for any set $F \in \Lambda$. This implies that $\delta(\varphi(s^*)) \geq \frac{1}{2}$ and $\delta(\varphi(s^*))$ nondecreasing in $\varphi(s^*)$. The same arguments apply to disagreements among producers and suppliers, regardless of the partitions. Therefore, the result holds for any set $F \in \Lambda$. \square

PROOF OF PROPOSITION 9. Suppose again without loss of generality that the efficient standard s^* is in the set S_A . Again for ease of notation, let $s_A = s^*$ and let s_B be any standard in S_B . It follows that $\varphi(s_A) > \varphi(s_B)$ and $q^M(\varphi(s_A), q_\mu, \bar{q}) \geq q^M(\varphi(s_B), q_\mu, \bar{q})$. If $q^M(\varphi(s_A), q_\mu, \bar{q}) < I - q^M(\varphi(s_B), q_\mu, \bar{q})$, there is no overlap between active distributors under the two standards. Because output depends on $\varphi(s^*)$, the number of votes for s^* , we can define $I^M(\varphi(s^*))$ as a function of $\varphi(s^*)$. It follows that $\frac{I^M(\varphi(s^*))}{I} > \frac{1}{2}$.

If $q^M(\varphi(s_A), q_\mu, \bar{q}) = q^M(\varphi(s_B), q_\mu, \bar{q}) = \bar{q}$. If $\bar{q} = I < \min\{H, J\}$, all distributors are active and profits are $v_i(s_A) = v_i(s_B) = \eta(\bar{q}) - \eta(I - i)$. So, $i^* = 1/2$ and

$\frac{I^M(\varphi(s^*))}{I} = \frac{1}{2}$. If $\bar{q} = H < \min\{I, J\}$ or $\bar{q} = J < \min\{H, I\}$, and $\bar{q} \geq I - \bar{q}$, $i^* = 1/2$ and $\frac{I^M(\varphi(s^*))}{I} = \frac{1}{2}$.

If $q^M(\varphi(s_A), q_\mu, \bar{q}) = \widehat{q}^M(\varphi(s_A))$ and $q^M(\varphi(s_B), q_\mu, \bar{q}) = \widehat{q}^M(\varphi(s_B))$. Then, $v_i(s_A) = \eta(\widehat{q}^M(\varphi(s_A))) - \eta(i)$ and $v_i(s_B) = \eta(\widehat{q}^M(\varphi(s_B))) - \eta(I - i)$. Then,

$$\eta(i^*) - \eta(I - i^*) = \eta(\widehat{q}^M(\varphi(s_A))) - \eta(\widehat{q}^M(\varphi(s_B))) > 0.$$

So, $i^* > 1/2$ and $\frac{I^M(\varphi(s^*))}{I} > \frac{1}{2}$.

If $q^M(\varphi(s_A), q_\mu, \bar{q}) = q^M(\varphi(s_B), q_\mu, \bar{q}) = q_\mu$. So, $v_i(s_A) = v_i(s_B) = \eta(q_\mu) - \eta(i)$, and $i^* = 1/2$ and $\frac{I^M(\varphi(s^*))}{I} = \frac{1}{2}$. If $q^M(\varphi(s_A), q_\mu, \bar{q}) = \bar{q}$ and $q^M(\varphi(s_B), q_\mu, \bar{q}) = q_\mu$ so that $v_i(s_A) = \eta(\bar{q}) - \eta(I - i)$ and $v_i(s_B) = \eta(q_\mu) - \eta(i)$. Then,

$$\eta(i^*) - \eta(I - i^*) = \eta(\bar{q}) - \eta(q_\mu) > 0.$$

So, $i^* > 1/2$ and $I(s^*) > \frac{I}{2}$. If $q^M(\varphi(s_A), q_\mu, \bar{q}) = \bar{q}$ and $q^M(\varphi(s_B), q_\mu, \bar{q}) = \widehat{q}^M(\varphi(s_B))$, then $i^* > 1/2$ and $I(s^*) > \frac{I}{2}$. Finally, if $q^M(\varphi(s_A), q_\mu, \bar{q}) = \widehat{q}^M(\varphi(s_A))$ and $q^M(\varphi(s_B), q_\mu, \bar{q}) = q_\mu$, then $i^* > 1/2$ and $\frac{I^M(\varphi(s^*))}{I} > \frac{1}{2}$. This implies that $\frac{I^M(\varphi(s^*))}{I} \geq \frac{1}{2}$. The same result holds for producers and suppliers, regardless of the partitions. Therefore, the result holds for any set $F \in \Lambda$. \square

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