Choosing the Rules for Consensus Standardization *

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Abstract

Consensus standardization often involves bargaining without side payments or substantive compromise, creating a war of attrition that selects through delay. We investigate the tradeoff between screening and delay when this process selects for socially valuable but privately observed quality. Immediate random choice may outperform the war of attrition, or vice versa. Allowing an uninformed neutral player to break deadlocks can improve on both mechanisms. Policies that reduce players' vested interest, and hence delays, can strengthen the *ex ante* incentive to improve proposals. JEL Codes: L15, C78, D71, D83.

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1 Introduction

In Standard Setting Organizations (SSOs) firms seek voluntary consensus on aspects of product design so that different products can work together. This process mingles technical discussion and political negotiation, in contrast to *de facto* standards wars where firms race for market share, compete to attract complements, and battle for user expectations. Engineers often hope, and sometimes think, that the consensus process is a collaborative search for the best solution. But firms often have strong vested interests in particular technologies, and there may be no effective mechanism for compromise. This makes it hard to achieve consensus, and turns the coordination problem into a war of attrition: proponents argue for their preferred solution, or simply hold out, until one side concedes.

We show how the war of attrition can select for the technically best solution, but imposes delays when there is vested interest. We then analyze its theoretical performance compared to alternative (weaker) notions of consensus. In our model, it is often efficient to interrupt the war of attrition and make a random choice, either immediately or after a period of screening. If commitment to random choice is institutionally awkward, the SSO in our model can achieve the same result by giving an uninformed but neutral participant the power to break deadlocks. Finally, policies that reduce vested interest, including intellectual property licensing rules, can reduce delays while preserving screening, and need not weaken players' *ex ante* incentive to improve proposals.

Though motivated by compatibility standards, our model could be relevant to any institution that seeks consensus among parties with private information who cannot use side-payments or substantive compromise to reach an agreement.[1]

[1] Other examples of consensus-seeking institutions might include legislatures, multi-national fora such as the World Trade Organization or United Nations, and the various not-for-profit consortia used to create metrics for product quality, safety, and corporate labor or environmental practices.

Standard Setting Organizations

SSOs promote technical coordination by replacing (or complementing) the bandwagon *de facto* standards process with an orderly explicit search for consensus.[2] Active participants incur direct costs such as membership, staff support and travel.[3] This can induce a free-rider problem, encouraging over-representation by firms with vested interests in a particular solution (Weiss and Toyofuku, 1996; Osborne et al., 2000). For technology standards, vested interests often arise through leads in product development, the presence of an installed base or (increasingly) intellectual property rights.[4]

In principle, an SSO could choose any decision mechanism to select a standard: taking into account members' information, their incentives to participate, the level of vested interest, and the need to produce standards that will attract widespread support. However, SSOs generally seek *consensus*, which the International Organization for Standardization (ISO) defines as:

> "general agreement, characterized by the absence of sustained opposition to substantial issues by any important part of the concerned interests and by a process that involves seeking to take into account the views of all parties concerned and to reconcile any conflicting arguments." (ISO/IEC *Directives* 2004, page 26)

Although economists might view monetary transfers as a natural route to consensus, SSOs do not encourage that. Because consumers are seldom at the table, antitrust issues could arise if firms paid each other to agree to proposed standards — especially when they implicate participants' intellectual property. Side-payments could also inefficiently encourage submission of weak proposals in order to get bought

[2]We use the term SSO to include both formally accredited standards developing organizations (SDOs) and less formal standards forums and industry consortia.

[3]Estimates of these costs vary widely. (Siegel, 2002, page 227) suggests that "a medium to large end-user corporation will invest $50,000 per year" per SSO in salary, travel, and membership fees; and that firms who "contribute" technology may spend considerably more. Both Hewlett Packard and Sun Microsystems belonged to more than 150 SSOs in 2003 (see "Major Standards Players Tell How They Evaluate SSOs," Andrew Updegrove, Consortium Standards Bulletin, June 2003). Chiao et al. (2007) cite a Forbes magazine article suggesting that IBM spent $500 million on standards-related activities in 2005.

[4]The trade press contains numerous accounts of vested interest, such as "Zapping the Competition: How companies are using obscure standards-setting bodies to cripple new technologies and hog-tie rivals" (Scott Woolley, Forbes, October 2, 2006) or "UWB Standards Group Calls it Quits," (Mark Hachman, Computerworld, January 19, 2006). Eisenman and Barley (2006) quote one participant on the matter of development lead times: "... there is tremendous resistance from other companies, who say 'Why should I endorse something that you're ready to ship and give you a time-to-market lead?'" The March 2007 *Consortium Standards Bulletin* (http://consortiuminfo.org/bulletins) offers a practitioner's view of intellectual property issues.

out.

Substantive compromise may provide an alternative to monetary side-payments. For instance, standards sometimes include "vendor specific options" to allow for product differentiation. But there is no guarantee that technical compromise will be efficient, and at some point participants are often forced to make a clear choice between competing alternatives.[5]

When the consensus principle enables each participant to hold up an agreement, and side-payments or compromise are unavailable or ineffective, bargaining becomes a war of attrition that selects a winner through costly delay. Thus, Davies (2004) describes consensus decision-making at the Internet Engineering Task Force:

> "A single vocal individual or small group can be a particular challenge to Working Group progress and the authority of the chair. The IETF does not have a strategy for dealing effectively with an individual who is inhibiting progress, whilst ensuring that an individual who has a genuine reason for revisiting a decision is allowed to get his or her point across."

Similarly, Sun Microsystems' former director of standards (Cargill, 2001) claims that "[the] formal process — with its Byzantine structures, considerable delays for review, reconsideration, and re-vote... can take up to 48 months to complete, resulting in lost market opportunity." [6]

Outline

We develop a model of the war of attrition with private information on the quality of sponsors' proposals. In Section 2, we show that the symmetric equilibrium of a war of attrition selects the better proposal, and calculate the delay involved; the key parameter is a measure of vested interest. Section 3 explores the welfare tradeoff between selection and delay, showing when immediate random choice outperforms the war of attrition, and that a delayed random choice may outperform either. We also show

[5]Similar issues arise in other settings. Roth (2007) describes a variety of cases where ethical norms or "repugnance" present a significant obstacle to monetary transactions. Powell (2004) surveys a literature that emphasizes dynamic commitment problems as a source of bargaining failures in government formation.

[6]Many SSOs have adopted "fast track" procedures and strive to reduce administrative delays, but most still take several years to approve a significant standard. For example, the 1999 *Annual Report* of the International Electrotechnical Commission (IEC) claimed that 20 percent of standards were developed in less than three years, "in direct response to industry requests that we speed up the standardization process." (By comparison, the 1991 *Annual Report* indicated a mean development time of 87 months (page 6)).

that SSOs could implement optimally delayed random choice by using a neutral participant to break deadlocks. Section 4 analyzes implications for sponsors' incentives to develop and improve their proposals. The uninterrupted war of attrition provides relatively weak incentives for innovation. However, because improvements to the losing proposal cause longer delays, these weak incentives may still be socially excessive. By reducing delays, policy changes that reduce vested interest may strengthen the incentives to develop good proposals in the first place.

Related Literature

Farrell and Saloner (1988) first modeled consensus standard setting as a war of attrition. Their complete-information analysis with mixed strategies predicts that a consensus process is more likely to achieve coordination than decentralized adoption, but that on average it is slow, and in a symmetric setting is outperformed by immediate random choice. Random choice, however, picks a random standard, while (as we show) a war of attrition could select for technological quality. To address that possibility we introduce private information on the quality of proposals, and evaluate how well, and how promptly, the process selects one.

David and Monroe (1994) also use the war of attrition to study SSOs, but in their model there is no trade-off between delay and the quality of outcomes. Our setup is closer to Bolton and Farrell (1990), who study entry in natural monopoly markets when firms have private information on costs. They find that decentralized entry selects the low cost firm more often than immediate random choice, but also leads to delays and duplication, so neither mechanism is always preferred. Unlike that model, we assume an element of common interest — all payoffs depend (positively) on the winner's type — and show that delays become negligible as vested interest disappears. We also use our model to analyze the role of third parties in consensus decision-making, and to evaluate *ex ante* incentives to improve proposals.

The war of attrition has been used to describe biological competition (Smith, 1974; Riley, 1980), labor strikes (Kennan and Wilson, 1989), the decision to exit a market (Fudenberg and Tirole, 1986), the road to war (Fearon, 1994), and a variety of picturesque applications (Bliss and Nalebuff, 1984). Bulow and Klemperer (1999) and Myatt (2005) use standard-setting as a motivating example of the war of attrition, but do not focus on the issues we examine. Krishna and Morgan (1997) make the formal link between a war of attrition and the second-price all-pay auction. Our model is equivalent to an all-pay auction with positive externalities (Jehiel and Moldovanu, 2000), in a setting where revenues (i.e. delays) are costly.[7] To our knowledge, it is the first model to introduce a third player who may endogenously intervene to conclude a war of attrition.

This article also contributes to a public-choice literature on consensus decision rules, which are typically modeled as unanimity (e.g. Buchanan and Tullock, 1965). Li et al. (2001) study the incentive for committee members to distort private information under a consensus rule, and Maggi and Morelli (2006) show that unanimity may be optimal in a repeated game with complete-information binary voting against the status quo. We evaluate the performance of a consensus rule when players have private information about competing alternatives, each of which is known to dominate the status quo, and vested interests make cheap talk impossible.

Lerner and Tirole (2006) develop an alternative model of SSOs in their role as a certifier, rather than a forum for reaching consensus. In their theory, SSOs differ in their degree of sympathy for technology vendors relative to end-users, and vendors choose the friendliest SSO whose certification will persuade end-users to adopt the standard. Chiao et al. (2007) use data on SSO procedures to verify that sponsor-friendly SSOs require weaker licensing commitments.

Although early empirical research on SSOs was primarily case-based,[8] quantitative studies are becoming more common. For example, Bekkers et al. (2002) combine case research with descriptive data analysis to show how the patent portfolios and alliance network of firms participating in the European Telecommunications Standards Institute (ETSI) evolved over time. Rysman and Simcoe (2008) use patent citations

[7]There is an extensive literature on bargaining delays. In addition to time-based signalling, as in the war of attrition, bargaining delays can occur when disagreement payoffs are endogenous (Fernandez and Glazer, 1991; Busch and Wen, 1995), when there are externalities (Jehiel and Moldovanu, 1995), when the size of the pie is stochastic (Merlo and Wilson, 1995), or when there is learning about bargaining power (Yildiz, 2004).

[8]Case studies of compatibility standard setting include Besen and Johnson (1988), Besen and Saloner (1989), Foray (1995), Lehr (1995) and Eisenman and Barley (2006). Weiss and Sirbu's (1990) quantitative analysis of the determinants of successful proposals is a notable exception.

to study the impact of SSO endorsements on demand for the standardized technology. Leiponen (2008) studies log-rolling when participants meet in multiple SSOs. And Simcoe (2012) combines a complete information model of SSO bargaining with empirical evidence that Internet commercialization caused a slowdown in standard setting at the Internet Engineering Task Force. Many recent empirical studies are motivated by debates over SSO intellectual property policies (Bekkers et al., 2011; Contreras, 2011; Layne-Farrar and Padilla, 2011) and the relationship between SSOs and patent pools (Layne-Farrar and Lerner, 2011; Baron and Pohlmann, 2010).

2 A Model of Consensus

Two proponents offer solutions; each ($i = 1, 2$) has a privately known quality q_i drawn from the continuous distribution $F(q)$ with support $[q_{min}, \infty)$. The game ends when one player concedes, agreeing to the other's proposal. We assume there is no scope for compromise or side payments.

Player i's strategy is a concession time t_i, meaning that he will concede at t_i if $j \neq i$ has not yet conceded. If $t_1 < t_2$ then player 1 actually concedes at time t_1, and as of that date gets a payoff of Lq_2, whereas player 2 gets Wq_2, where $L > 0$ and $W > 0$ measure the "loser's" and "winner's" shares of the total surplus.[9] If $t_1 = t_2$ each player wins with probability $\frac{1}{2}$. The players share a discount rate r, flow payoffs are zero until agreement is reached, and $q_{min} > 0$, so both players prefer a new standard to the status quo. Thus, when $t_1 < t_2$ the players' *ex ante* payoffs are $\Pi_1(q, t) = e^{-rt_1} Lq_2$ and $\Pi_2(q, t) = e^{-rt_1} W q_2$.

Though motivated by the war of attrition, these payoffs could be implemented as a second-price all-pay auction with an endogenous consolation-prize: each player "bids" a concession time, both pay a waiting cost determined by the smaller bid, and both receive a prize that is proportional to the winner's type. Because the loser's payoff depends on the winner's type, this game has an element of common interest that is absent in the standard war of attrition. In the extreme case where $L = W$, it is a

[9]We do not normalize $W + L = 1$ as Section 4 considers policies that may influence W independently of L, e.g. licensing rules that allow the winner to capture more consumer surplus.

team game where both participants want the lower-quality player to concede.[10] More realistically, as we assume henceforth, $W > L$: there is "vested interest." Thus, each player would like its proposal adopted, even if its rival has somewhat higher quality, but would concede if it knew that a rival's quality was more than W/L times better than its own. Although players with a high q would like to reveal that information, vested interest makes their rival skeptical.[11]

Screening and Equilibrium

We focus on symmetric perfect Bayesian equilibrium: a concession-time strategy $t(\cdot)$, such that a player of type q finds it optimal to concede at time $t(q)$ if its rival has not yet conceded and if it believes its rival is using the same strategy.[12] If proposal qualities are independently distributed, it is well known that equilibrium concession strategies $t(\cdot)$ are increasing in proposal quality.[13]

Lemma 1 *When qualities are independently distributed, every rationalizable Bayesian strategy is weakly increasing.*

Lemma 1 is intuitive: a player's expected payoff from concession is independent of its own type (quality), whereas its expected payoff from holding out longer increases with its type.[14] Because qualities are drawn from the continuous distribution $F(q)$, symmetric equilibrium concession strategies are one-to-one. Thus, we have

Proposition 1 *When qualities are independently and continuously distributed, the symmetric equilibrium of an uninterrupted war of attrition selects the better proposal.*

As is well known, the war of attrition also has asymmetric equilibria, including a pair of equilibria where one player concedes immediately because the other never

[10] As a result, they could resolve the issue through cheap talk. We show below that in the limit as W and L converge, the war of attrition also achieves full screening with no delay.

[11] In practice, information on customer behavior or demand for a particular technology may be important but hard to verify. Even technical performance, which might seem easy to observe, can be controversial when there are many relevant dimensions.

[12] Appendix A shows that third-party intervention (introduced in Section 3) leads to a unique equilibrium, which is symmetric in the *ex ante* symmetric case.

[13] Versions of this result are in Bliss and Nalebuff (1984, Theorem 2), Fudenberg and Tirole (1991, page 217) and Bulow and Klemperer (1999, Lemma 1).

[14] Proofs not contained in the text are collected in an Appendix that is available on the authors' web sites.

concedes. In our model, common interest can rule out such extreme asymmetries. Specifically, Proposition A-1 (in Appendix A) shows that for any equilibrium of our model, the ratio of any type of player 1 and type of player 2 that would concede at a given time must lie between L/W and W/L. Intuitively, the faster a player concedes, the larger must be its opponent's opportunity cost of delay. Consequently, expectations of "tough" behavior (i.e. slow concessions) are not amplified, as can happen in the "standard" war of attrition, reputational bargaining games (Abreu and Gul, 2000) and common value auctions (Bulow et al., 1999).

Because the costs of delay in our model depend on a rival's expected quality, it is helpful to define the expected type of a player whose type is at least x:

$$G(x) \equiv \mathrm{E}[q|q \geq x] = \frac{\int_x^\infty s \, \mathrm{d}F(s)}{1 - F(x)}.$$

To characterize equilibrium when concession strategies are strictly monotonic, define $\beta(t) = q$, the inverse of the $t(\cdot)$ function, and consider a type q player who, in equilibrium, will concede at time $t(q)$, yielding (as of then) expected payoff $LG(q)$. If this player were instead to hold out a short time $\mathrm{d}t$ longer before conceding, its expected payoff as of $t(q)$ would be

$$[h(q)\beta'(t)\,\mathrm{d}t]\,Wq + e^{-r\,\mathrm{d}t}\,[1 - h(q)\beta'(t)\,\mathrm{d}t]\,LG(q + \beta'(t)\,\mathrm{d}t),$$

where $h(q)$ is the hazard rate $f(q)[1 - F(q)]^{-1}$. The first-order condition, equating marginal costs and benefits of delay (and suppressing arguments for brevity), is:

$$rLG = h\beta'Wq + LG'\beta' - h\beta'LG \tag{1}$$

and substituting $G'(q) \equiv h(q)[G(q) - q]$ into equation (1) yields

$$rLG = h\beta'[W - L]q \tag{2}$$

Intuitively, the marginal cost of delay is rLG, and the marginal benefit is the probability that a rival concedes in the next instant $(h\beta')$ multiplied by the change in payoffs, given that concession reveals the rival to have type q.

To solve for equilibrium strategies, define a measure of vested interest $v \equiv \frac{(W-L)}{L} \geq 0$, and write $K(x) \equiv G(x)[1-F(x)] = \int_x^\infty s\,\mathrm{d}F(s)$. Note that $G(q_{min}) = K(q_{min}) = \mu$, the *ex ante* average quality, and that $K'(s) = -sf(s)$. Rearranging equation (2) yields

$$\frac{1}{\beta'} \equiv \frac{\mathrm{d}t}{\mathrm{d}q} = \frac{vqh(q)}{rG(q)} = \frac{vqf(q)}{rK(q)} \tag{3}$$

This differential equation, together with the boundary condition $t(q_{min}) = 0$, defines a unique symmetric Bayesian equilibrium,

$$t(q) = \frac{v}{r}\int_{\underline{q}}^{q} \frac{sf(s)\,\mathrm{d}s}{K(s)} = \frac{v}{r}[\log\mu - \log K(q)] \tag{4}$$

or in terms of the time value of delay until q concedes,

$$\delta(q) \equiv e^{-rt(q)} = \left[\frac{K(q)}{\mu}\right]^v \tag{5}$$

3 Performance: War of Attrition vs. Random Intervention

We now ask whether the war of attrition's screening properties make it a desirable standard setting mechanism, given the costs of delay. We measure performance as the players' expected payoffs. Although this approach does not explicitly account for non-participants' welfare, the interests of participants and non-participants are often broadly but imperfectly aligned.[15] From equation (5) it immediately follows that r affects the time to agreement but not present-value payoffs as of $t = 0$.

Proposition 2 *The ex post (and hence interim and ex ante) performance of the symmetric equilibrium of a war of attrition is independent of r. Delays are increasing in vested interest v. When v approaches zero, so do delays, and performance approaches first-best.*

[15] Participants bear the direct costs of standardization, which may lead to free-riding. On the other hand, participants can have incentives to design or influence the process so as to increase their joint rents, e.g. by setting substantial licensing fees for the standard or using the process to exclude rent-destroying new technology.

Proposition 2 says that for low v, a war of attrition selects the best proposal at low cost.[16] Appendix B describes several policies that SSOs use to reduce v, including starting early, before firms become attached to a particular solution; endorsing partial or "incomplete" standards that allow for product differentiation; and adopting disclosure rules asking participants to reveal relevant patents.

For large v, our model predicts long delays. Performance is especially poor if both players draw good proposals, yielding long delays and little *ex post* value from screening. Moreover, Proposition 2 may be too optimistic if willingness to wait depends on factors other than quality. The remainder of this section asks whether participants might trade screening for speed by committing to a well-timed random choice *ex ante*, while they are still ignorant of their own proposal quality.

To model random intervention, we introduce a neutral player that shares the proponents' discount rate r and whose present-value payoff once a standard is chosen is Bq, where $B > 0$ is an arbitrary constant. This player knows the game and parameters, but not the proposal qualities, and can only decide how long (T) to let the war of attrition continue before choosing a winner at random.[17] Two special cases are the war of attrition itself (never intervene, $T = \infty$), and immediate random choice (intervene immediately, $T = 0$).

One might think of the neutral player as an SSO participant with a pivotal vote. Many SSOs have policies to encourage neutral participants, and allow a specified super-majority to approve standards.[18] The neutral player could also represent a bystander with enough clout to bypass the SSO and jump-start market adoption, such as a large end-user, a "platform leader" (Cusumano and Gawer, 2002) or a government agency that would defer to a timely consensus recommendation from industry. We focus on a symmetric random intervention, where each sponsor is chosen

[16] This result may be generalized in various ways, including allowing for affiliated proposal qualities, following Krishna and Morgan (1997), or more than two players, as in Bulow and Klemperer (1999).

[17] We assume the neutral player can accept concessions that occur at T, and selects each sponsor with probability $\frac{1}{2}$ in the event of a tie.

[18] To promote a balance of interests, ANSI's Essential Requirements states that "Participants from diverse interest categories shall be sought with the objective of achieving balance" and describes several broad categories of participant, including producers, users, consumers, and general interest (e.g. academic) members (American National Standards Institute, 2006, page 6). Of course, each of these groups may have their own rent-seeking incentives. Examples of super-majority voting include ISO, which requires a two-thirds majority of "P-member" votes (IEC/ISO *Directives*, part 1, section 2.4.3.), and OASIS (a consortium that develops software standards), which allows two-thirds of the membership to approve a proposal provided no more than twenty-five percent object.

with probability $p = \frac{1}{2}$, but only require that both sponsors have a strictly positive chance of winning.

Equilibrium with random intervention

The proponents' concession strategies will generally respond to anticipations of T. Nevertheless, we begin by analyzing the neutral player's choice of T as if proponents would continue playing the strategies derived in the uninterrupted war of attrition.

Fixed Concession Strategies (FCS): *If proponents expect a random choice at T, then their equilibrium concession strategies remain unchanged (i.e., as if $T = \infty$).*

Assumption FCS would of course be true if random intervention were unanticipated. As we show below, FCS is also true when the proponents expect an intervention at T^*, the *optimal* time for a surprise intervention.

When screening ends at $t_{min} \equiv \min\{T, t(q_1), t(q_2)\}$, the neutral player's expected payoff is $Be^{-rt_{min}}G(\beta(t_{min}))$, and his optimal strategy (under FCS) will put mass only on the value(s) of T that maximize that payoff. Thus, the expected value of waiting slightly longer before intervening is

$$Be^{-rT}\{G'(\beta(T))\beta'(T) - rG(\beta(T))\} \tag{6}$$

Substituting β' from (3) reveals that a neutral player prefers a bit more screening to immediate intervention if and only if

$$G(q) - (1 + v)q > 0 \tag{7}$$

If (7) holds for all q, then (under FCS) a neutral player will never want to intervene, because the war of attrition screens so efficiently. If (7) never holds, the war of attrition screens so slowly that delay is never desirable, and the neutral player should make an immediate random choice. Both of these extreme cases are possible:[19]

[19] Details of this and subsequent examples, all based on the Pareto distribution, are provided in the online Appendix.

Example 1 *Suppose quality has the Pareto distribution* $F(q) = 1 - q^{-(1+a)}$ *for* $q \geq 1$. *Under assumption FCS, a neutral player makes an immediate random choice if* $av > 1$ *and allows an uninterrupted war of attrition if* $av < 1$.

In general, neither (7) nor its reverse will hold globally. When $G(q) - (1 + v)q$ crosses the axis from above exactly once, at say q^*, the neutral player's expected payoff (under FCS) is single-peaked as a function of T, so he prefers the war of attrition until $T^* = t(q^*)$ and immediate random choice thereafter. Bagnoli and Bergstrom (2005, Theorem 6) prove that $G(q) - q$ is decreasing when either $f(q)$ or $1 - F(q)$ is log-concave, which holds for many common probability distributions, including the uniform, normal, exponential and logistic.[20] Thus we have:

Lemma 2 *Under FCS, if either* $f(q)$ *or* $1 - F(q)$ *is log-concave, there is a unique time* $T^* \geq 0$ *such that a neutral player prefers screening via the war of attrition at all* $t < T^*$ *and immediate random choice thereafter.*

That is, for log-concave quality distributions, screening is efficient at small values of q (or t), but not large values. To see how the social benefits of screening relate to the private benefits of delay, re-write the sponsor's first-order condition (1) as

$$L(G'\beta' - rG) + h\beta'(Wq - LG) = 0 \tag{8}$$

The first term is proportional to the marginal social benefits of delay, as in (6). The second term reflects a sponsor's vested interest "wish to win" as of time t; it is the probability that the other sponsor concedes in the next instant, times the change in (interim) expected private payoff if that happens. Perhaps surprisingly, this interim "wish to win" is negative when $Wq < LG(q)$, as winning brings news that rival quality is much worse than expected. And because (8) is a sponsor's first-order condition, the two terms must cancel for the type meant to concede at t. Thus, we have:

Lemma 3 *In a symmetric equilibrium, the marginal proponent prefers concession to*

[20] With $v > 0$, the Bagnoli-Bergstrom result implies that $G(q) - (1 + v)q$ is strictly decreasing. In failure analysis $G(q) - q$ is called the mean-residual-life function. It gives the expected time-to-failure of a machine that has already run for q. If this function is decreasing, then a machine "ages" or wears out over time.

immediate victory if and only if screening is locally efficient: $W\beta(t) < LG(\beta(t))$ *if and only if* $G'(\beta(t))\beta'(t) > rG(\beta(t))$.

As promised above, we now justify assumption FCS by showing that it holds if players expect a random choice at T^*.

Proposition 3 *The following strategies are a perfect Bayesian equilibrium: Sponsor-types* $q < q^*$ *use the concession strategy derived in Section 2.1. Types* $q > q^*$ *never concede. The neutral player waits until* T^* *before making a random choice (and would also intervene at all times* $t > T^*$*).*

To understand this result, note that by Lemma 3, $Wq^* = LG(q^*)$: the type q^* who is meant to concede at T^* is (at that time) indifferent between concession and an immediate random choice. Players of lower type would prefer to concede. If (contrary to equilibrium) they waited until T^*, they would then scurry to concede rather than risk "winning", because for them, $Wq < LG(q^*)$. Players of higher type, for whom $Wq > LG(q^*)$, would rather win than concede at T^*, so they will not want to pre-empt the random intervention. Other potential deviations are unprofitable just as they were without the prospect of random choice: their marginal costs and benefits have not changed. Finally, if the game has continued (out-of-equilibrium) past T^*, remaining types will not concede, as the neutral player's specified strategy is then immediate random intervention, which they prefer to concession.

Before proceeding, we offer several remarks about this equilibrium. First, although log-concavity guarantees a unique T^*, Proposition 3 holds for general quality distributions as long as random intervention is locally optimal. Second, the neutral player's threat of intervention at all $t > T^*$ is credible even if sponsors have weaker off-equilibrium beliefs. For example, a neutral player should intervene after T^* if the war of attrition would otherwise continue indefinitely (as it would under FCS), rather than "stalling" at T^* because sponsors expect a random choice at any moment. Finally, totally differentiating (7) shows that $\frac{\mathrm{d}q^*}{\mathrm{d}v} < 0$: the optimal amount of screening is decreasing in vested interest.

Uniqueness

Proposition 3 shows that random intervention at T^* is an equilibrium: it is optimal given that proponents expect it. We now show that intervention at T^* is the unique perfect Bayesian equilibrium: it is the only time that a neutral player could optimally intervene, given the proponents' optimal response.

To begin, consider a sponsor that anticipates random intervention at T. This player could wait for the random choice, concede at T, or drop out earlier. Monotonicity (Lemma 1) implies that these strategies are ranked: the lowest types concede according to their first-order condition (derived in Section 2.1), intermediate types may try a "last minute" concession at T, and the highest types wait for a random choice.

Lemma 4 *When proponents expect a random intervention at $T < \infty$, their symmetric equilibrium concession strategies have thresholds $\underline{q} \leq \overline{q}$, such that types $q < \underline{q}$ concede according to $t(q)$; types $q \in (\underline{q}, \overline{q})$ concede at T; and types $q > \overline{q}$ wait for the random intervention.*

Now consider the neutral player's best response. When $T > T^*$ we must have $\underline{q} > q^*$, because Lemma 3 says that types below q^* would rather concede at $t(q)$ than wait for the random intervention. However, in that case the neutral player would prefer to intervene at T^*: further delays are costly, and the threat of intervention leads types above q^* to concede more slowly (on average) than under assumption FCS. Since this is a contradiction, any perfect equilibrium must have $T \leq T^*$.

When $T < T^*$, we must have $\underline{q} < q^*$, as there is not enough time for all types below q^* to concede at $t(q)$. Furthermore, we can infer that $\overline{q} < q^*$, becuase type q^* strictly prefers a random intervention unless all lower types have conceded by T, and in this hypothetical equilibrium types $q \in (\underline{q}, q^*)$ have not dropped out. However, when $\overline{q} < q^*$ the neutral player prefers to renege on the intervention, as types in $[\overline{q}, q^*)$ will screen efficiently in a symmetric equilibrium where $\overline{q}$ is the lowest remaining type. Although this temptation to renege would not exist if the remaining sponsors would screen very slowly, we can apply Lemma 4 to the sub-game starting at T to show that for *any* off-equilibrium beliefs about the timing of a subsequent random intervention, the lowest remaining sponsor-types will concede at least as quickly as they would in an uninterrupted war of attrition. As it is not possible to sustain the sponsors' belief in a random intervention at $T < T^*$, we conclude that:

Proposition 4 *Proposition 3 describes the unique symmetric Bayesian equilibrium of the game with endogenous intervention.*

Proposition A-2 shows that endogenous intervention always selects a unique equilibrium, which need not be symmetric in the *ex ante* asymmetric case.

Our analysis leaves open the possibility that a neutral player could improve on the outcome of Proposition 3 by committing to an earlier deadline.[21] Unfortunately, the analysis of this case is complex and we do not know whether that possibility can occur. In practice, it may be difficult for SSOs to commit to an arbitrary deadline, particularly when an explicitly random decision would jeopardize *ex post* adoption.[22] In contrast, allowing neutral participants to break deadlocks can reduce delay while preserving a less demanding version of consensus.

4 Innovation Incentives

Above, we took the distribution of q to be exogenous. We now ask whether policies that reduce screening or lower v would reduce sponsors' incentives to develop better solutions in the first place.

War of attrition versus random choice

A player's interim expected payoff in the uninterrupted war of attrition can be found by accounting for outcomes as a function of its rival's type:[23]

[21]In principle, a neutral player with commitment power might do even better by choosing a more complex mechanism that specifies waiting times and the probability of winning as a function of sponsors' reported types. We hope to pursue that approach in future work.

[22]Taken literally, Proposition 3 suggests that an N-player standards committee should accept any proposal that can gather two or more votes; because any sponsor who has already conceded could serve as the tie-breaker. However, a naive "two-vote rule" would be easy to manipulate if competing proposals are typically sponsored by coalitions that vary in size and influence. And though random choice may seem tempting when the standards process is painfully slow, formalizing that decision rule could encourage the submission of low quality proposals.

[23]An alternative derivation of $u(q)$ starts from (10) and uses the boundary condition $u(q_{min}) = L\mu$. Integrating by parts, $u(q) = L\mu + W \int_{q_{min}}^{q} \delta(s)f(s)[q-s]\,\mathrm{d}s$. Thus, the "information rents" in this model are a weighted average of differences between a player's own type q and all worse types.

$$u(q) = Wq \int_{q_{min}}^{q} \delta(s)\,\mathrm{d}F(s) + \delta(q)G(q)\left[1 - F(q)\right] \tag{9}$$

If this player's rival cannot observe its quality improvements, its interim incentive to improve q is $u'(q)$. From the envelope theorem, this equals the gain from an increase in q holding its own (as well as its rival's) concession strategies fixed:

$$u'(q) = W \int_{q_{min}}^{q} \delta(s)\,\mathrm{d}F(s) \tag{10}$$

This describes the incentive to un-observably improve quality that is now q. For a simple model of *ex ante* incentives, suppose that players choose effort e that increases quality by e whatever the realization of q, so the cumulative quality distribution becomes $F^*(q;e) \equiv F(q-e)$. Because the marginal benefit of effort is equivalent to a small increase in quality $\mathrm{d}q$, taking expectations over q measures the (gross) *ex ante* innovation incentive in an uninterrupted war of attrition: $I^{WOA} \equiv \mathrm{E}[u'(q)]$.[24]

Now consider incentives to improve q under several interpretations of random choice. First, a predetermined standard-setter's payoff is Wq, so its incentive to improve quality is $I^{\mathrm{PS}} = W$.[25] This player's rivals have no incentive to develop or propose technologies.[26] Second, if random choice represents a "rough and ready" selection process, where each player wins immediately half of the time, then each player has *ex ante* innovation incentive $I^{\mathrm{RC}} = \frac{1}{2}W$. Finally, if a neutral player will break deadlocks through random intervention at T^*, then interim incentives to un-observably improve quality (I^{RI}) are a combination of the previous cases: sponsor-types $q < q^*$ have the same incentives they would in a war of attrition, and those with $q \geq q^*$ will face a delayed symmetric random choice whenever their rival also waits till T^*. The following proposition compares innovation incentives under these four different

[24] We analyze unobserved quality improvements for two reasons. First, in some applications, including ours, it may be unrealistic to assume that R&D inputs are observed by rivals while outcomes are private information. And second, if we assume endogenous intervention by a neutral participant – which ensures a unique equilibrium at the consensus-seeking stage – the marginal benefits of R&D are discontinuous because the stochastically stronger player is always selected (see Proposition A-3 in the Appendix). This suggests that innovation incentives are strong when efforts to improve quality are observed, but also leads to mixed-strategy equilibria in the *ex ante* signaling game.

[25] These incentives are still below the fully efficient level $I^{\mathrm{FE}} = W + L$, and do not explicitly reflect users' interests.

[26] Given the pre-determined standard setter, this demotivation of others is efficient in our model. In general it can be desirable to give one player a strong incentive to innovate, and others none, if innovation is costly but needs no imagination. In other cases it may be better to give some incentive to each of many potential innovators.

arrangements.

Proposition 5 *If the marginal benefit of unobserved ex ante R&D is constant in q, a predetermined standard setter has the strongest incentive to innovate, followed by firms facing an immediate random choice. Firms that anticipate a random intervention at $T^* > 0$ have weaker incentives than under immediate random choice, but stronger than under an uninterrupted war of attrition:* $I^{\mathrm{PS}} = W > I^{\mathrm{RC}} = \frac{1}{2}W \geq I^{\mathrm{RI}} \geq I^{\mathrm{WOA}}$.

Intuitively, a player gains from an increase in its own q if and only if it is the winner. This accounts for the comparison between a predetermined standard setter and an immediate random choice. Next, the war of attrition gives each player the same *ex ante* probability of winning as random choice, but delays payoffs (and by longer if it is uninterrupted) thus reducing the expected slope of $e^{-rt}Wq$ conditional on eventual victory. One might expect offsetting rent-seeking "competition" in quality, but in the model each player could act as if its quality were higher (conceding later and winning more often) without actually changing its quality. So the war of attrition produces weaker incentives than immediate or delayed random choice.[27]

Reducing vested interest

We now consider policies that would reduce delay without interrupting the war of attrition. Proposition 2 says that delays are increasing in v. However, innovation incentives depend on W and L, not only via v, and policies may affect both W and L. For instance, allowing a winning sponsor to exploit its patents without limits after a standard is locked in will transfer surplus from end-users to the sponsor, and may also hurt other participants, but plausibly not as much as the winning sponsor gains. We model such changes as a shift in payoffs from (W, L) to $(W + \mathrm{d}W, L - k\,\mathrm{d}W)$ for some $k \geq 0$.[28]

In our model, increasing W raises private returns to innovation directly, whereas increasing v reduces them by increasing delay. On balance, increasing vested interest

[27] Cabral and Salant (2008) develop a model where standardization may occur *before* firms have a chance to innovate, and improvements to a shared standard benefit all players equally. In their model, firms may delay choosing a standard to prevent free-riding in R&D.

[28] The case $k > 1$ corresponds to where stronger patent rights reduce total industry rents, as may occur if the patent thicket problem (Shapiro, 2001) is severe. Appendix B comments briefly on the issue of patents in standards.

can either raise or lower incentives to innovate:

Example 2 *In the uninterrupted war of attrition with a Pareto distribution, I^{WOA} is increasing in W if and only if $k < \frac{a+2}{a(v+1)^2}$.*

For the Pareto distribution, a pure transfer from consumers to the winning sponsor ($k = 0$) will increase the *ex ante* incentive to improve proposals. With small enough v, even policies that re-distribute from losers to winners ($k = 1$) will encourage innovation. But when v is large, policies that reduce L will discourage innovation by increasing delay.

Proposition 6 *In the uninterrupted war of attrition, policies that reduce vested interest may raise or lower ex ante incentives to improve the distribution of q.*

Private and social incentives to innovate

Finally, we compare private to social innovation incentives in the uninterrupted war of attrition. Conditional on player 1 having type q, the total expected surplus in an uninterrupted war of attrition is

$$s(q) = (W + L)\left\{q \int_{q_{min}}^{q} \delta(y)\,\mathrm{d}F(y) + \delta(q)\int_{q}^{\infty} y\,\mathrm{d}F(y)\right\}$$

By (10), the change in interim surplus from slightly improving q is:

$$s'(q) = (W + L)\left\{\frac{u'(q)}{W} - vq\delta(q)f(q)\right\} \tag{11}$$

As (11) suggests, under a war of attrition interim social returns to improving a low-quality proposal can be negative: improving an eventually losing proposal merely delays its concession. By contrast, as (10) shows, interim private incentives to improve quality go to zero but remain positive as $q \to q_{min}$.

Improving an already high-quality proposal, on the other hand, confers a positive externality: the other player, already likely to lose, loses to a better proposal. Thus, interim private incentives are excessive for low-quality proposals, but insufficient for high-quality proposals. Taking expectations over q, we can ask which of these effects dominates *ex ante*.

Example 3 *If $F(\cdot)$ has a Pareto distribution, then $E[s'(q)] < E[u'(q)]$ if and only if $v(v+2)(a+1) > 1$: private incentives to improve quality are too high if there is strong vested interest.*

Thus we have:

Proposition 7 *In an uninterrupted war-of-attrition, private incentives to improve the ex ante distribution of q may be greater or less than is socially optimal. Interim incentives to improve q are too strong for low-quality proposals and too weak for high-quality proposals.*

In general, allowing some vested interest may be optimal for innovation. However, because increasing v increases delay without improving screening, SSOs should set v below the level that would provide optimal innovation incentives if delays were not an issue. Moreover, Proposition 7 implies that policies to reduce v may (by reducing delays) generate stronger innovation incentives.

5 Conclusion

Motivated by the formal standards process, we study bargaining between privately informed parties with competing proposals whose adoption requires consensus. Although the economics literature on bargaining stresses side payments and substantive compromise as routes to agreement, those paths are not always used. We model institutions where participants may hold out for their preferred solution, delaying consensus until one side concedes, and use this model to evaluate the resulting delay relative to random choice.

In our simple model, the war of attrition discriminates well, but is slow. With strong vested interest, it can be more efficient to stress speed at the expense of screening for quality — perhaps by relaxing the concept of consensus and encouraging neutral participants to break deadlocks. The model also suggests that when vested interest is strong, policies that limit vested interest may even increase the incentive to improve proposals.

We addressed these issues using a simple model of SSO negotiations. Future work might also pursue a complementary methodology, along the lines of mechanism design, that would lay out the informational and incentive constraints in more detail and characterize optimal incentive-compatible decision-rules.

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Appendix A

To model an asymmetric standards committee, we assume the same players, actions and payoffs described above, but let each proponent $i = 1, 2$ have a different quality distribution $F_i(q)$. These distributions are common knowledge. The neutral player can intervene to select a winner at any time $T \geq 0$, but this intervention is no longer random: they will select the proponent with higher expected quality given the equilibrium concession strategies and any delay that has already occurred. Lemmas 1 and 4 extend to the asymmetric case with one slight difference: there may now be an atom of concessions at $t = 0$.[29]

Lemma A-1 *When qualities are independently distributed, every rationalizable Bayesian strategy is weakly increasing. If proponents anticipate an intervention at $T < \infty$, then there exists a time $\bar{t} \leq T$ such that concession strategies are strictly increasing on the interval $[0, \bar{t})$, and the only times when there may be an atom of concession are $t = 0, T$.*

To characterize the sponsors' strictly increasing concession strategies for $t \in [0, \bar{t})$, define the inverse stopping rules $\beta_i(t) = q_i$; the expected quality of a proponent whose quality is at least x, $G_i(x) \equiv \frac{\int_x^\infty s \, \mathrm{d}F_i(s)}{1 - F_i(x)}$; and the hazard rate $h_i(q) = \frac{f_i(q)}{1 - F_i(q)}$. As in Section 2.1, we can derive player i's first-order condition

$$rLG_j(q_j) = LG'_j\beta'_j(t) + h_j\beta'_j(t)[Wq_i - LG_j] \tag{A-1}$$

$$= h_j\beta'_j(t)[Wq_i - Lq_j] \tag{A-2}$$

where, for brevity, we have written q_i in place of $\beta_i(t)$, the type of player i that concedes at t given that j concedes according to $t_j(q)$. This pair of first-order conditions leads immediately to the following generalization of Proposition 2:

Proposition A-1 *In any equilibrium, for all $t > 0$ the ratio of marginal types $\beta_i(t)/\beta_j(t)$ must lie in the interval $(\frac{L}{W}, \frac{W}{L})$. As W approaches L (no vested interest), delays disappear and the performance of the war of attrition approaches first-best (instant screening).*

Proof: Note that $rLG_j > 0$ and $h_j > 0$. So, in order for both β_1 and β_2 to be increasing functions of t, the pair of first-order conditions (A-2) imply that $q_i \equiv \beta_i(t) \in (\frac{L}{W}\beta_j(t), \frac{W}{L}\beta_j(t))$ for both players at all $t \in (0, \bar{t})$. Thus, in the limit as $W \to L$, we have $\beta_i(t) = \beta_j(t)$, which implies perfect screening. Moreover, this screening is instantaneous in the limit, since $\beta'_i \to \infty$ as the term $[Wq_i - Lq_j]$ on the right side of equation (A-2) approaches zero. □

Proposition A-1 shows that common interest can rule out highly asymmetric equilibria in the uninterrupted war of attrition. However, the remaining equilibria need not be unique, except for

[29]See Myatt (2005) for detailed proofs that are readily adapted to our model.

the limiting case where $L = W$. We now show that endogenous intervention by a neutral player selects an essentially unique equilibrium.[30] We begin by showing that there are no gaps or atoms in the distribution of equilibrium concession times. This justifies using the neutral player's first-order condition to find the optimal time for intervention (as we did above under Assumption FCS). The unique equilibrium is characterized by the proponents' first order conditions (A-1) and a pair of boundary conditions at T^*, the optimal time to intervene.[31]

Lemma A-2 *In any equilibrium with endogenous intervention, there are no gaps in the distribution of concession times. There is also no atom of concessions at T for any player whose proposal has a positive probability of being selected should neither concede.*

Proof: Lemma A-1 implies that the only possible gap in concession times occurs between $\bar{t}$ and T. In that case, the neutral player would deviate by intervening at $\bar{t}$: it remains an equilibrium for any proponent that would have conceded at T to drop out at $\bar{t}$, and moving the intervention forward makes all players strictly better off.

Now suppose player i has an atom at T. Define the probability of concession $\theta_i = F_i(\overline{q_i}) - F_i(\underline{q_i})$, and the expected quality of types that concede $E_i = \frac{1}{\theta_i}\int_{\underline{q_i}}^{\overline{q_i}} s dF_i(s)$. If both sponsors concede at T, the neutral player selects each with probability $\frac{1}{2}$, and if neither concedes player i wins with probability p, where $p = 1$ whenever $G_i(\overline{q_i}) > G_j(\overline{q_j})$. Given these strategies, player i's expected payoff from conceding at T is $\Pi_i(q, T) = \theta_j \frac{1}{2}[Wq + LE_j] + (1-\theta_j)LG_j(\overline{q_j})$, and its expected payoff from waiting is $\Pi_i(q, \infty) = \theta_j Wq + (1-\theta_j)[pWq + (1-p)LG_j(\overline{q_j})$. We claim that if $p > 0$ then $\theta_i = 0$. There are two cases to consider: $p = 1$ and $p \in (0, 1)$.

First, if $p = 1$ and $\theta_i > 0$ then all remaining types of player j must concede at T (otherwise, they are guaranteed to lose). By assumption, types $q_i > \overline{q_i}$ wait for the intervention and receive Wq_i, and types in the interval $(\underline{q_i}, \overline{q_i})$ concede at T to receive $\Pi_i(q, T)$. The continuous payoffs and support of F_i imply that type $\overline{q_i}$ must be indifferent between conceding at T and waiting, which implies that $W\overline{q_i} = LG_j(\underline{q_j})$. Similarly, for all types $q_i < \underline{q_i}$ to willingly concede before T we must have $\Pi_i(\underline{q_i}, T) = LG_j(\underline{q_j})$, which implies that $W\underline{q_i} = LG_j(\underline{q_j})$. However, if $W\underline{q_i} = LG_j(\underline{q_j}) = W\overline{q_i}$, then $\theta_i = 0$, because $\underline{q_i} = \overline{q_i}$.

Now suppose $p \in (0, 1)$ and $\theta_i > 0$. Solving $LG_i(\underline{q_i}) = \Pi_j(\underline{q_j}, T)$ reveals that $W\underline{q_j} = LE_i$. Solving $\Pi_j(\overline{q_j}, T) = \Pi_j(\overline{q_j}, \infty)$ reveals that

$$W\overline{q_j}[(1-\theta_i)(1-p) + \frac{1}{2}\theta_i] = LG_i(\overline{q_i})(1-\theta_i)(1-p) + \frac{1}{2}\theta_i LE_i \quad \text{(A-3)}$$

[30] We say the equilibrium is essentially unique because a player that loses for certain at T will be indifferent between conceding at that time and waiting for the neutral player to select their opponent.

[31] As with the standard war of attrition, assuming that $t_i(q_{min}) = 0$ when $q_{min} = 0$ does not provide a suitable pair of boundary conditions, because the proponents' first-order conditions (A-1) are not Lipschitz continuous at $q_i = q_j = 0$ (Fudenberg and Tirole 1986).

Equation (A-3) has two useful implications. First, given that $G_i(\overline{q_i}) > E_i$ by assumption, it implies that $W\overline{q_j} > LE_i = W\underline{q_j}$, so there must be an atom of concessions by player j. Second, equation (A-3) implies that $W\overline{q_j} < LG_i(\overline{q_i})$; if neither sponsor concedes at T, the lowest remaining type of player j would rather concede than win. The same must be true for player i. To complete the proof, we argue that if the lowest remaining type of each sponsor would rather concede than win, the neutral player will not intervene.

Lemma A-1 implies that in any sub-game starting at T, the sponsors must concede at least as fast as they would in a war of attrition. Thus, if the neutral player delays intervention for an instant before selecting player i, the marginal benefits are *at least* $G_i'\beta_i' + h_i\beta_i'[G_j - G_i]$, and the marginal costs are $rG_i(\overline{q_i})$. Because $p < 1$ implies $G_i(\overline{q_i}) = G_j(\overline{q_j})$, the neutral player will prefer delay to intervention whenever $G_i'\beta_i' > rG_i$. However, the sponsor's first-order conditions (A-1) imply that $G_i'\beta_i' > rG_i$ whenever $W\overline{q_j} < LG_i(\overline{q_i})$. Thus, delay strictly dominates intervention for the neutral player when neither proponent concedes at T. If sponsors cannot reasonably expect an intervention at T, there can be no equilibrium where $p \in (0, 1)$ and $\theta_i > 0$. □

Proposition A-2 *Endogenous intervention by a neutral player selects a unique perfect Bayesian equilibrium to the war of attrition.*

Proof: Define $q_i^* = \beta_i(T)$, and assume (without loss of generality) that $G_i(q_i^*) \geq G_j(q_j^*)$, so the neutral player weakly prefers to select player i's proposal. Because there are no atoms for player i, we know that $Wq_i^* = LG_j(q_j^*)$: higher types of player i strictly prefer any intervention where they have a positive probability of winning, and lower types prefer concession.

Now consider the neutral player's stopping problem. The marginal cost of delay is rG_i, and (by Lemma B2) the marginal benefit of waiting another instant is $G_i'\beta_i' + h_i\beta_i'[G_j - G_i]$, so the neutral player's first-order condition is

$$rG_i(q_i^*) = G_i'\beta_i' + h_i(q_i^*)\beta_i'[G_j(q_j^*) - G_i(q_i^*)]$$

Substituting player j's first order condition from (A-1) into this expression and using the identity $G' = h[G - q]$ reveals that $Wq_j^* = LG_j(q_j^*)$. Thus, we now have

$$Wq_j^* = LG_j(q_j^*) = Wq_i^* \leq LG_i(q_i^*) \tag{A-4}$$

and the neutral player must choose i's proposal if the final inequality is strict.

Log-concavity implies a unique solution q_j^* to the first equality in (A-4), and therefore a unique pair of equilibrium quality thresholds $q_j^* = q_i^*$. Given these quality thresholds, we can solve for T by integrating the players' first-order conditions "from the top." In particular, given that the proponents' concession strategies are invertible on $t \in (0, T)$, the time required to screen types in the interval (x, q_i^*) is given by

$$\tau_i(x) = \int_x^{q_i^*} \frac{1}{\beta_i'} dq = \int_x^{q_i^*} \frac{h_i(q)[W\beta_j(t_i(q)) - Lq]}{rLG_i(q)} dq$$

In equilibrium we will have $\tau_i(\beta_i(t)) = \tau_j(\beta_j(t))$ for all t, and the optimal time for an endogenous intervention is given by $T = \lim_{t\to 0} \tau_i(\beta_i(t))$. $\square$

As in the symmetric case, log-concavity implies a unique $T^* > 0$, although Proposition A-2 holds for general quality distributions. The proposition also implies that in any equilibrium with endogenous intervention, we have $\beta_j(T) = \beta_i(T)$: the last type of each proponent to concede will have the same quality. The latter observation leads immediately to

Proposition A-3 *In any equilibrium with endogenous intervention, if F_i first-order stochastic dominates (or hazard rate dominates) F_j, the neutral player will always select player i as the winner.*

Proposition A-3 implies that in a model with endogenous intervention, the returns to observable efforts to improve the quality distribution are discontinuous. In particular, suppose that e_i measures player i's R&D effort, and that the quality distribution $F_i(q|e_i)$ dominates $F_j(q|e_j)$ whenever $e_i > e_j$ (e.g. when F_i is a Poisson distribution with dispersion parameter $\lambda_i = e_i$). Starting from a symmetric equilibrium, where the neutral player intervenes at T and selects each sponsor with probability $\frac{1}{2}$, a small increase in e_i will cause the neutral player to select player i with certainty, but produce only a small change in the distribution of concession times. Because the signaling benefits of R&D overwhelm its direct impact, the only equilibria to this *ex ante* investment game will be in mixed strategies: player i will always prefer to invest a bit more than e_j when j's effort is known.

We conclude this appendix by showing that when quality distributions can be ranked in terms of hazard rate dominance, there is a strictly positive probability of "instant exit" at $t = 0$ by the weaker player, as in Myatt (2005). Perhaps surprisingly, this implies that the stochastically stronger player concedes faster (i.e. a larger set of types drop out between $t = 0$ and $t = T$). But the intuition for this result is now familiar: the stronger player's lowest types would rather concede than win, given the weaker player's expected quality, which is higher as a consequence of the instant exits.

Proposition A-4 *In any equilibrium with endogenous intervention, if F_i hazard rate dominates F_j there is an atom of concessions by player j at $t = 0$.*

Proof: If the distribution $F_i(q)$ hazard rate dominates $F_j(q)$, then (by definition), $h_i(q) < h_j(q)$ and $G_i(q) > G_j(q)$ for all $q \in [\underline{q}, \infty]$. Proposition A-3 implies that the neutral player will select player i's proposal. The proponents' first-order condition (A-1), together with hazard-rate dominance, imply that

$$\beta_i'(T) = \frac{rLG_i(q^*)}{h_i(q^*)[W-L]q^*} > \frac{rLG_j(q^*)}{h_j(q^*)[W-L]q^*} = \beta_j'(T)$$

so the stochastically stronger player is conceding faster at the moment of intervention. Because the stronger player is conceding faster at T, we can infer that $\beta_j(t) > \beta_i(t)$ for all $t \in (0, T)$. If not, there would be some t such that $\beta_j(t) = \beta_i(t)$ and $\beta_j'(t) > \beta_i'(t)$, which would contradict the assumption of hazard rate dominance. Finally, $\beta_j(0) > \beta_i(0) = q_{min}$ implies that there is an atom of concessions at $t = 0$ consisting of player j's lowest types. $\square$

Appendix B

Broadly speaking, policies that reduce v, or change the structure of the game (e.g. by introducing side-payments or substantive compromise) should speed up the screening process. Reforms that leave vested interest and the underlying war-of-attrition structure untouched are unlikely to improve matters in the same way.

Anticipatory standards

Vested interests are growing all the time as installed bases grow or proprietary knowledge develops. As when one sets off on a commute just before rush-hour, every delay in starting means a bigger delay in finishing. Thus, some observers urge "anticipatory standardization" in advance of the market, before vested interests grow strong. Standardizing in advance seems likely to reduce v, and hence delays, but to reduce both the opportunities for product development and the reliability of screening for quality. It could thus be viewed as a move towards random choice.

Some practitioners suggest that parallel efforts can limit the cost of technological short-sightedness and preserve the benefits of starting before vested interest sets in. For example, Updegrove describes the development of multiple wireless standards:[32]

> "The difficulty of predicting the future when setting anticipatory standards is clearly demonstrated by the example of early wireless data standards development. HomeRF disappeared, Bluetooth found a home in one set of short-range applications, and Wi-Fi predominated for longer distances... over time, it became clear which standard was optimally useful within areas of overlap."

When multiple efforts do not overlap, the parallel approach preserves technological flexibility, though it is likely to create a future demand for converters. However, when rival firms commit to competing technologies, parallel efforts can *increase* vested interest in the final push for a common

[32] "Is One Standard Always Better than Two?," Andrew Updegrove, Consortium Standards Bulletin, 18 December 2005.

standard. For example, the IEEE's 802.15.3a committee disbanded after three years of work when rival factions, each with its own consortium, could not reach a compromise on protocols for ultra-wideband wireless networking.[33]

Incomplete standards

In practice, formal standards do not always ensure compatibility: not every two "conforming" products are inter-operable. In particular, standards sometimes include incompatible or "vendor-specific" options; partly in response to the uncertainty about feasibility, cost, and demand that results from standardizing early, but also as a way to reduce vested interest. For instance, Sirbu and Zwimpfer (1985) describe how incompatible options were included in the X.25 packet switching standard in order to placate intractable vested interest. Similarly, Kolodziej relates that an impasse in negotiating PC modem standards (V.42) was overcome by deciding "to put both protocols into the standard."[34]

The result is a "model" — an incompletely-specified standard, or menu of choices — meant to ensure a baseline level of inter-operability. When firms make different choices from the menu, their products may not be fully compatible. Nevertheless, a model can help in achieving compatibility. It may be easier to choose a profile within a model than develop a standard from scratch: not all options need be included, and uncontroversial issues may be standardized. Moreover, it can be easier to patch together compatibility through converters within a model than it would be without the model. For example, although every Internet device shares a common networking protocol (TCP/IP), the Internet's various physical networks use different transport protocols and communicate with each other through a series of converters (gateway protocols) developed and maintained by the IETF.

Intellectual property rules

Many SSOs adopt intellectual property (IP) policies, whereby participants promise to disclose relevant patents and license on "reasonable" terms any that are essential to comply with a standard.[35] These rules can reduce the risk of hold-up, in which a firm fails to disclose its IP until others have substantially committed to the standard, weakening them in license negotiations.[36] Licensing rules limit participants' use of their IP once it is embedded in an industry standard, typically requiring licensing on "reasonable and non-discriminatory" (RAND) terms.[37] To the extent that RAND rules

[33] "UWB Standards Group Calls it Quits," Mark Hachman, Computerworld, January 19, 2006.

[34] "Egos, Infighting and Politics: Standards Process bogged Down," Stan Kolodziej, *Computerworld*, September 7 1988, pp. 17-22.

[35] Lemley (2002) and Chiao et al. (2007) survey SSOs' IP policies; Teece and Sherry (2003) and Farrell et al. (2007) discuss these policies in antitrust terms; see also American Bar Association (2003), or United States Department of Justice and Federal Trade Commission (2007).

[36] The FTC has taken action against several firms, including *Dell Computer* (FTC No. 931-0097) and *Rambus* (FTC Docket No. 9302) for various versions of hold-up.

[37] ANSI requires sponsors to offer patent licenses either "without compensation" or "under reasonable terms and conditions that are demonstrably free of any unfair discrimination." (American National Standards Institute, 2006,

commit SSO participants to liberal licensing (there is some controversy about the legal interpretation of such rules) these policies will lower W, and likely raise L, thus reducing v.

Recently, a few SSOs (notably VITA and IEEE) have started to encourage *ex ante* disclosure of maximum allowable royalty rates, which already takes place in some cases (see for instance the FTC's complaint in *NData*). In our model, these commitments provide a negotiating tool that resembles side-payments.

Meeting more often

Committees charged with developing a consensus standard typically meet only periodically. A natural initiative toward reducing delays is meeting more often. Presumably, this provides more time to work out technical issues; and, once consensus emerges, more frequent plenary or official meetings to finish the process can help. But to the extent that, as in the model, the work is largely bargaining, the time to agreement is determined by screening constraints, and meeting more often is unlikely to reduce delays. Indeed, our model assumes perpetual meetings; but the delays persist. Of course, frequent meetings would reduce the time to consensus if they increase the flow costs of delay to participants. But if firms simply locked their negotiators into a room and waited, those agents might behave more like a neutral player, counter to the private interests of the competing sponsors.

As this reasoning suggests, SDOs may have had more success in accelerating post-consensus administrative processing than in speeding consensus. In its 1994 *Annual Report* (page 4), the IEC noted that, "Time for the fundamental part of standards production — preparatory and technical development stages... has remained substantially the same, while time for the latter stages of approval and publication... has been brought down by 60 percent."

Appendix I). Some SSOs require royalty-free licenses: for instance, the World Wide Web Consortium (W3C) adopted a royalty-free policy in 2005. Other SSOs require that licenses also be "fair", creating the alternative acronym FRAND.