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Standardization in Decentralized Economies

By EMMANUELLE AURIOL AND MICHEL BENAÏM*

This paper presents a dynamic model, inspired by evolutionary game theory, of how standards and norms emerge in decentralized economies. It shows that standardization outcomes depend on adopters' attitudes to problems caused by incompatibility. If individuals display aversion to incompatibility, standardization never fails to happen eventually, but societies sometimes end up picking inferior standards. In this case, official action can be useful to quickly achieve sensible standardization. On the other hand, when individuals display tolerance or neutrality to incompatibility, there is neither path-dependency nor a lock-in problem, and regulation seems a poor alternative to laissez-faire. (JEL C73, D62, L1)

On the threshold of the twenty-first century, the globalization of market economies is gathering speed with international trade growing four times as fast as the economy. In this new economic environment, there is an increasing need for standardization and conformity assessment systems to come to span previously separated jurisdictions. Internationally accepted standards are necessary, first, to facilitate product comparisons and reduce technical barriers to trade¹ and, second, to allow for better quality management and consumer protection. More than 500 organizations work with the International Organization for Standardization, ISO, on

the setting of standards.² Domestic organizations often duplicate this international activity. For instance, in the United States, there are more than 700 organizations trying to promote their own, sometimes contradictory, specifications for adoption as standards. The proliferation of these organizations illustrates the importance of the standardization issue and helps to explain the difficulty of managing it successfully. In a world where technologies are constantly evolving and information about preferences is widely dispersed, setting standards is a tricky business. The consensus in the United States and ISO is to rely on de facto market forces. Many in the European Union (EU), because of a political commitment to unification, favor a more centralized approach to standard setting.

This paper analyzes the process of standardization in decentralized economies. It highlights the conditions under which centralized intervention is desirable and those where, on the contrary, laissez-faire seems preferable. The analysis is conducted in the spirit of evolutionary game theory to take account of the dynamic nature of standard adoption. Showing how adopters' attitudes toward incompatibility affect

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¹ Numerous studies have documented large price differences between separated markets for the same good. Among the reasons for this persistent segmentation between national markets is the existence of different product standards (World Bank, 1998).

² The ISO standardization process, which is decentralized, involves some 2,850 technical committees and 30,000 experts. It relies on market forces and is based on consensus. ISO is not an acronym, but rather a word formed from the Greek-based prefix *iso-*, meaning "equal." This has the convenient side effect of allowing the organization to be called the same thing in all languages. (www.iso.ch [1999]).

the outcome of a decentralized standardization process is the main contribution of the paper.

Aversion to incompatibility occurs if coordination failures are costly to users. This is the case with traffic regulations and signs, electrical norms, and drug formulas. People display little tolerance to incompatibility when their safety is at stake. If adopters fear standardization failures, they will attempt to avoid them. In the presence of aversion to incompatibility, we show that the decentralized adoption process inevitably leads to a single standard being established. Still, it is not always possible to predict which standard will end up being selected. If the alternatives are not very different, adopters sometimes coordinate on an inferior one. Since *laissez-faire* can lead to inefficient outcomes, an official intervention helps to quickly achieve sensible standardization. In every country in the world there are traffic rules, electrical norms, and other mandatory standards intended to protect users' health and safety. The European Committee for Standardization, U.S. Consumer Product Safety Commission, and U.S. Food and Drug Administration are examples of agencies whose role is to promote such performance standards.

Neutrality to incompatibility holds when there are direct coordination externalities. This covers one-to-one communication equipment such as telephone, facsimile, and computer networks. These goods provide direct links between users. Since making a connection requires that the parties use compatible technologies, achieving standardization is important. More subscribers using a particular standard increases the chance of being able to communicate for all those using that standard. Under neutrality to incompatibility, we show that a decentralized standards adoption process always leads to selection of the best one. Common standards among the world's telephone, facsimile, and computer networks should come as no surprise. This standardization outcome maximizes social welfare.

Tolerance to incompatibility occurs if there are indirect coordination externalities. Examples include items like personal computers, music players, and VCRs. Here, consumers care about compatibility because the availability of complementary goods depends on sales of the primary good. As the quantity of available videos, compact disks, tapes, or software increases, consumers tend to lose interest in the number of other users. Individuals then pick the technology that happens to

suit them best. It should not be surprising that a decentralized adoption process occasionally results in a multiple-standard equilibrium. In the presence of tolerance to incompatibility, we show that adoption of a single standard is no longer systematic, or even necessarily optimal. Users take their time and experiment. Only the dominant technology can emerge from the standardization process as the unique choice.

From an empirical point of view, the results are consistent with the evidence on diffusion curves of new technologies, which are known to be S-shaped. The diffusion curves obtained from our theoretical analysis are also S-shaped. This is true regardless of individuals' attitudes toward incompatibility. Whether there is aversion, neutrality, or tolerance makes no difference here. Moreover, our paper gives particular insights into the comparative benefits of decentralization and regulation in the setting of standards. When there is a public-safety issue at stake, this calls for regulation or mandatory standardization. In the presence of aversion to incompatibility, official intervention is necessary to hasten coordination while preventing moves toward inferior standards. On the other hand, in the presence of tolerance or neutrality with respect to incompatibility, there is no risk of either "lock-in" or safety hazards. This is in contrast to the risk that regulators or "experts" might misrepresent consumers' tastes and needs. Regulation, at least in the early stages of the adoption process, seems a poor alternative to experimentation by users.

Relationship with the Literature.—The classic economic literature relies on noncooperative game theory to address the standardization issue.³ This literature provides a comprehensive study of producers' behavior in the presence of network externalities, leaving the demand side of standard adoption a black box. Consumers are assumed to simultaneously adopt one of the available standards. Positive coordination externalities then

³ Initiated by the Joseph Farrell-Garth Saloner (1985) and Michael L. Katz-Carl Shapiro (1985) papers, the "network externalities" literature deals with standardization issues from the standpoint of the Nash equilibrium concept. For an appraisal of this literature, see the symposium on Network Externalities in the *Journal of Economic Perspectives* (1994 Vol. 8).

generate multiple equilibria. In most cases, the authors characterize equilibria analytically, but fail to solve what W. Brian Arthur (1988) calls the *selection problem*. In pioneering papers, Arthur (1988, 1989) proposes to address this issue by using stochastic models. His idea is that coordination externalities tend to magnify “historical events”—the *path-dependency* property—and trap the dynamics in a possibly dominated standard—the *lock-in* property. Arthur’s seminal contribution highlights the fact that, standardization generally being the result of a sequence of decentralized choices, history matters. However, he also suggests, through the examples he develops, that the alternative to regulation is a highly unpredictable, path-dependent decentralized process. This contradicts the intuitive perception that market-driven standardization is not all *that* unpredictable or inefficient. There remains the question of how independent, heterogeneous individuals actually coordinate their choices, that is to say, how a particular equilibrium comes to prevail.

This question lies at the core of the growing literature on evolutionary game theory and social learning, the aim of which is to study equilibrium selection in games that have multiple equilibria. This literature explains how an equilibrium can emerge as a result of learning or adaptation, rather than from rational introspection.⁴ Kandori et al. (1993), in a by-now classic paper, have shown that symmetrical games (involving large numbers of myopic players and noisy mutations) naturally lead players, who hesitate between two Nash equilibria, to select the risk-dominant one. This contribution has been a major step in the area of equilibrium selection. Their result holds independently of any initial conditions or “historical events.” More importantly, from our point of view, it has opened the door to a predictive theory of coordination problems in dynamic settings.

In the spirit of this original and fruitful line of research, this paper focuses on the coordination

problem faced by heterogeneous individuals who have to choose between two standards. There are two time scales: a short one for individuals and a longer one for societies as a whole. The dynamic dimension is captured by the fact that individuals adopt one or the other standard sequentially and in a random order. The two time scales—individual and social—are captured by the fact that “new-born” adopters who inherit a state of standardization from their predecessors are not forward-looking. Their limited life span requires them to optimize in the short run. One may wonder whether successive myopic adoptions will lead to some kind of unconscious collective maximizing behavior or, on the contrary, to pure path-dependency. The answer depends on the particular standard at stake.

We show that in the long run the stochastic decentralized process of adoption behaves like a deterministic dynamic one. Since in its static version the coordination problem admits multiple equilibria, introducing the dynamics solves the selection issue. Only stable equilibria of the associated deterministic process can emerge in the long run. An important aspect of our paper is then to highlight the role concavity or convexity of the individuals’ utility functions plays in equilibrium selection. Contrary to the Kandori et al. (1993) setting, and to all other settings of which we are aware, agents’ utilities are not necessarily linear with respect to the fraction of the population which chooses the same standard. We show that convexity corresponds to an aversion to incompatibility, and concavity to a tolerance for it. Linearity corresponds to neutrality. When individuals are averse to incompatibility, standardization eventually occurs. The standard that ends up being selected is not always predictable, though. The fact that the equilibrium is not necessarily unique implies that the decentralized process sometimes selects the inferior standard. These are the path-dependent and lock-in properties described by Arthur (1988). On the other hand, when individuals display tolerance for incompatibility, standardization is no longer systematic. The adoption process, however, is always predictable. Finally, when individuals are neutral toward incompatibility, the decentralized process leads to standardization on the dominant standard. From the standpoint of society, this is an optimal outcome.

The paper is organized as follows. Section I describes the model. Section II presents some

⁴ The founding papers of this promising literature include, among others, Dean Foster and Peyton Young (1990), Glenn Ellison (1993), Drew Fudenberg and David M. Kreps (1993), and Michihiro Kandori et al. (1993). For an up-to-date survey of the literature (and nice developments as well), see the book by Fudenberg and David K. Levine (1998): *The Theory of Learning in Games*.

general results about the convergence of the stochastic process. Section III derives the equilibria and diffusion curves. Section IV characterizes the optimal solution and contrasts this solution with the equilibria of Section III. Section V offers some concluding remarks.

I. The Model

We take a discrete-choice model with two incompatible standards from which to choose, A and B . Adopters have an inelastic demand for one unit of the “good.” Their preferences are parameterized by $\delta \in [0, 1]$, which we call a “type.” The δ term can be interpreted as determining the adaptation cost incurred by agents when they have to accept a (for them) imperfect standard rather than enjoying their ideal one, which would have been located at δ . That is, δ is the “distance” between the individual and standard A , located at point 0; $1 - \delta$ being the distance between the individual and standard B , located at 1. Moreover, adopters’ preferences for A or B depend on the market share enjoyed by each standard, denoted x_A and x_B respectively. The preferences of a type δ agent over standard k ($=A, B$) are represented by the utility functions $k \rightarrow (1 - \delta_k)u_k(x_k)$, where $\delta_A = \delta$ and $\delta_B = 1 - \delta$. The functions u_A and u_B are defined net of the price of purchasing the standard.⁵ It follows that a type δ agent prefers one combination of standard and market share to another if and only if it renders a higher utility to that agent:

$$(1) \quad (A, x_A) \succ_{\delta} (B, x_B) \Leftrightarrow \\ (1 - \delta)u_A(x_A) \geq \delta u_B(x_B).$$

⁵ Price can be either fixed or changing over time, as long as the *net* utility function satisfies Assumption 1. This covers not only nonproprietary standards (e.g., typewriter keyboard arrangements, screw threads, bank-card formats, paper sizes, rail-track gauges, and computer-file compatibility formats such as ASCII), but also many proprietary standards. Indeed, most standardization games do not allow for multiple winners so that price competition is fierce (i.e., is of the Bertrand type). For instance, in the VHS/Beta battle over videotape format, S. J. Liebowitz and Stephen E. Margolis (1995) show that both technologies always re-tailed at about the same price, so that price cannot be said to have played a discriminating role in consumers’ decisions.

Functions u_A and u_B , which are the same for all agents but are not necessarily equal to each other, satisfy the following assumption.

ASSUMPTION 1: $u_k(0) = 0$ and $u'_k(x) > 0 \forall x \geq 0$ ($k = A, B$).

According to Assumption 1, the higher the proportion of the population using a given standard, the greater the net benefit to each individual adopting it. In other words, there are positive network externalities. This assumption is consistent with the literature on learning and evolution in games. In all the papers, as in Kandori et al. (1993), the benefit that an agent derives from adopting a technology increases in the fraction of the rest of the population that also adopts it. However, in these papers, as well as in the network externalities literature, the payoffs are *affine* functions of market share. In the learning literature, where the payoff matrix is independent of players’ strategies (i.e., they affect the payoff probability but not the payoff itself), this assumption is natural. It is less convincing in a coordination game such as standard adoption, in which individual benefits depend directly on the fraction of the population that makes compatible choices. We consider any function u_k that satisfies Assumption 1, including both concave and convex ones.⁶

Let δ_L^t be the marginal consumer at time t ; i.e., the one who has no particular preference for either standard. By equation (1), δ_L^t is the solution to $(1 - \delta)u_A(x_A^t) = \delta u_B(x_B^t)$, that is:

$$(2) \quad \delta_L^t = \frac{u_A(x_A^t)}{u_A(x_A^t) + u_B(x_B^t)}.$$

We deduce that an agent δ , entering the market at date $t + 1$, chooses standard A if $\delta \leq \delta_L^t$ and standard B otherwise. This type of behavior is referred to as myopic, because the agent does not try to incorporate in his decision the way the

⁶ This paper also considers heterogeneous agents (i.e., not everyone has the same δ), whereas Kandori et al. (1993) consider homogeneous agents. That is, in Kandori et al. (1993), the payoff of adopting strategy $k = A, B$ is for all agents $\alpha_k + \beta_k x_k^t$ with $\beta_k > 0$. Moreover, our paper concerns network externalities among all agents, whereas interaction in Kandori et al. (1993) is strictly bilateral.

standard will evolve in the future. In practice, when consumers face a new adoption choice, they heavily discount the future, in great part because they anticipate the phenomenon of obsolescence. In this paper, we take the extreme view that the adopters' psychological discount factor is infinite. This implies that, conditional on the past, their adoption choice is deterministic.⁷ On the contrary, the law governing their entry (the sequence of adopters) is exogenous and random. "Nature" decides who will come next. Candidates for adoption are distributed over the interval [0, 1] according to a bounded density function $f(\cdot)$ whose cumulative distribution function is denoted $F(\cdot)$.

ASSUMPTION 2: δ is distributed over [0, 1] according to a bounded density $f(\cdot)$.

Hence, the probability that an individual entering at round $t + 1$ will adopt standard k is simply $P_A(x_A^t, x_B^t) = \text{Prob}(\delta \leq \delta_L^t)$ for standard A , and $P_B(x_A^t, x_B^t) = \text{Prob}(\delta > \delta_L^t) = 1 - P_A(x_A^t, x_B^t)$ for standard B . We deduce from Assumption 2 and equation (2) that

$$(3) \quad P_A(x_A^t, x_B^t) = F\left(\frac{u_A(x_A^t)}{u_A(x_A^t) + u_B(x_B^t)}\right).$$

It is easy to check that, under Assumption 1, the probability $P_k^t = P_k(x_A^t, x_B^t)$ increases in the market share of standard k (and thus decreases in the market share of the other standard). This is only natural, since individual decisions are shaped by positive coordination externalities. Let us now examine how successive adoption choices eventually aggregate into a collective choice.

⁷ Following the work by George Ainslie (1975), psychologists have emphasized "the decline in effectiveness of rewards, as the rewards are delayed from the time of choice," thus challenging the assumption of an exponential discount function. Parametric studies and experiments have even found *hyperbolic* discount functions for humans and some animals. In fact, consumers are not permanent and know this, so they optimize in the short run. For a review of the literature, see Ainslie (1992) and George Loewenstein and Drazen Prelec (1992). Interesting discussion of the assumption of myopic behavior can be found in Kandori et al. (1993) and Fudenberg and Levine (1998 Ch. 4).

II. Emergence of Macro-Structure: A (Path-Dependent) Strong Law Theorem

The dynamics of the model are as follows. Time is discrete and its horizon infinite. Period $t = 1, 2, \dots$ designates the t th round of adoption. The rate at which adopters arrive on the market is not important (except when looking at convergence time); the relevant time is not that of the clock, but rather that of events. At each adoption round, an agent identified by δ is randomly drawn from the population of adopters according to the probability density f . The sequence of adopters is exogenous and random. The adoption choice, though, is endogenous and deterministic. The agents make their choice among standards depending on their current market shares and their own particular preference. For a given individual δ at a given date $t + 1$, she will adopt A if $\delta \leq \delta_L^t$ and B otherwise.

Let $N_k^0 \geq 1$ be the initial number of adopters of standard k ($= A, B$). From a technical point of view, this can be any integer larger than one. For the purpose of the analysis, though, it seems natural to focus on two cases: N_A^0 and N_B^0 both small, as would be the case in the introduction of two variants of a new technology; and N_A^0 small with N_B^0 large (or vice versa), as when a new standard begins to challenge a long-established one. Moreover, let N_k^t denote the cumulative number of agents that have adopted standard k at time t , and N^t denote the cumulative number of adoptions that have occurred up to time t . Observe that $N^t = N_A^0 + N_B^0 + t$.

The market share of standard k at time t is $x_k^t = N_k^t/N^t$. Since from equation (3) P_k^t denotes the probability that standard k will be selected at round $t + 1$ of adoption, the dynamics of market share are given by the following equation:

$$(4) \quad x_k^{t+1} = \frac{1}{N^t + 1} \begin{cases} N_k^t + 1 & \text{with probability } P_k^t \\ N_k^t & \text{with probability } 1 - P_k^t. \end{cases}$$

Let $\alpha^t = \frac{1}{N^t + 1}$. Then system (4) can be rewritten in the form:

$$(5) \quad x_k^{t+1} = \begin{cases} (1 - \alpha^t)x_k^t + \alpha^t & \text{with probability } P_k^t \\ (1 - \alpha^t)x_k^t & \text{with probability } 1 - P_k^t. \end{cases}$$

We derive from system (5) the expected motion of market share with respect to the current state x_k^t . We get:

$$(6) \quad E(x_k^{t+1}|x_k^t) = x_k^t + \alpha^t(P_k^t - x_k^t).$$

The interpretation of equation (6) is straightforward. The market share of standard k increases in expectation if the probability of standard k being adopted is greater than its current market share. Otherwise, it declines; term $\alpha^t(P_k^t - x_k^t)$ is positive when $P_k^t > x_k^t$ and negative when $P_k^t < x_k^t$. Indeed, if the market share of one standard is much smaller than its probability of being adopted, then this standard will be chosen on average more than proportionally to its current market share, and thus its market share will grow. By the same reasoning, if the market share of one standard is much larger than its probability of being adopted, then this standard's market share will decline. Intuition suggests that the system reaches an equilibrium when adoption probability and market share equalize. This conjecture proves to be correct.

Let $\Delta^1 = \{(x, y); x \geq 0; y \geq 0 \text{ and } x + y = 1\}$ denote the *unit simplex*. The probability function $P = (P_A, P_B)$, derived from equation (3), maps the unit simplex of market shares into the unit simplex of probabilities. With the stochastic process (5), we associate the deterministic system defined on Δ^1 (unit simplex of market share), given by the following ordinary differential equation (ODE) with dots for time derivatives:

$$(7) \quad \dot{x}_k = P_k(x_A, x_B) - x_k \quad k = A, B.$$

Theorem 1 establishes that the vector of market shares $\mathbf{x}^t = (x_A^t, x_B^t)$ of system (5) converges toward the equilibria of the ordinary differential equation (7).

THEOREM 1 (Bruce M. Hill et al., 1980):

- (i) Suppose $P : \Delta^1 \rightarrow \Delta^1$, the probability function which maps the unit simplex of market shares into the unit simplex of probabilities, is continuous. Then the vector of market shares $\mathbf{x}^t = (x_A^t, x_B^t)$ converges with probability one to an equilibrium (x_A^*, x_B^*) of the ODE (7).
- (ii) Suppose P maps the interior of the unit simplex into itself, and that (x_A^*, x_B^*) is a stable equilibrium (as defined in the conventional way) of the ODE (7). Suppose also that the initial market share (x_A^0, x_B^0) belongs to the interior of the simplex. Then the process (x_A^t, x_B^t) has a positive probability of converging to (x_A^*, x_B^*) .
- (iii) Suppose (x_A^*, x_B^*) is an unstable equilibrium of the ODE (7). Then the process cannot converge to (x_A^*, x_B^*) with positive probability.

Instead of studying the convergence of the stochastic process (5), it is sufficient, by virtue of Theorem 1, to study the convergence of the associated deterministic system (7). To understand this point, assume that, at the beginning of the competitive process, the initial cumulative number of subscribers, N^0 , is small (the case of two new standards competing to become the market standard). Market-share movement is then dominated by sharp fluctuations. When the cumulative number of subscribers is small, each new adoption makes market share jump. However, the impact of each new adoption on market-share movement decreases with the number of adoptions: the first adopter has a dramatic impact, whereas the millionth one is negligible. This creates a dynamic dampening of randomness over time.⁸ Trapped by mass inertia, the stochastic process ends up being directed by the equivalent deterministic system (7). Figure 5a illustrates these fluctua-

⁸ This is in contrast to the dampening of the mutation rate in Kandori et al. (1993). They consider a stationary and ergodic model, in which the population is of fixed size and each agent occasionally mutates. That is, randomness about the fraction of agents that adopt each technology is added to the system by mutation. Hence x_i^t does not converge. However, by letting the mutation rate tend to zero as a comparative statics exercise and characterizing the limit of the ergodic distribution, selection of a particular technology is ensured.

tions and their dampening.⁹ It is worth noting that, in the case of quadratic utility functions, $u_A(x) = ax^2$ and $u_B(y) = by^2$, and uniform distribution, equation (7) gives the replicator dynamics for a homogeneous population playing a symmetrical 2×2 coordination game [i.e., with payoff: $\Pi(A, A) = a$, $\Pi(B, B) = b$, $\Pi(A, B) = \Pi(B, A) = 0$]. That is, equation (7) becomes: $\dot{x} = x(ax - (ax^2 + b(1 - x)^2))$. This paper thus offers new micro-foundation for the study of continuous-time replicator dynamics, which can be generated as the limit of a stochastic model with heterogeneous adopters in discrete time.¹⁰

As in classic game theory, fixed points are candidates for equilibrium. However, not all fixed points can be selected as equilibria: only stable ones are eligible. An equilibrium x_k^* of the ODE is locally stable if $P'_k - 1 \leq 0$ at x_k^* (it is locally unstable otherwise). According to equation (6), if the probability of a standard being adopted in the neighborhood of an equilibrium is larger than its market share, this standard will be adopted increasingly and will diverge from the equilibrium. Symmetrically, if the probability is smaller than its market share, it will tend to converge to the equilibrium. This implies that x_k^i will diverge from a locally unstable equilibrium, and it will tend to converge to a locally stable equilibrium.¹¹ If the deterministic system has a single stable fixed point, equilibrium is predictable. Whatever the initial conditions N_A^0 and N_B^0 , the system will converge to this fixed point. On the other hand, if the deterministic system has multiple stable fixed points, the outcome is unpredictable due to fluctuations at the outset. In this case, equilibrium will be path-dependent. However, depending on the initial conditions, it is possible to be more precise about the results. Let $\mathbf{x}^* = (x_A^*, x_B^*)$ be a stable equilibrium of (7). We define the basin of attraction of \mathbf{x}^* ,

denoted $B(\mathbf{x}^*)$, as the set of points \mathbf{x} whose forward trajectory for the ODE is attracted by \mathbf{x}^* . That is, $B(\mathbf{x}^*) = \{\mathbf{x} \in \Delta^1 | \lim_{t \rightarrow \infty} \mathbf{x}(t) = \mathbf{x}^*\}$, where function $\mathbf{x}(t)$ denotes the solution of equation (7) with initial condition $\mathbf{x}(0) = \mathbf{x}$ (\mathbf{x} is the vector of initial market shares). The following theorem follows from Benaim (1999).

THEOREM 2: *Let $\mathbf{x}^* \in \Delta^1$ be a stable equilibrium of the ODE (7). Let $Q \subset B(\mathbf{x}^*)$ be a compact subset of the basin of attraction of \mathbf{x}^* . There exists a positive number k , uniquely dependent on Q , such that: If, at time $\tau \geq 0$, the total number of adoptions is $N^\tau = N_A^\tau + N_B^\tau$, and the market-share vector (x_A^τ, x_B^τ) belongs to Q , then*

$$\text{Prob}\left(\lim_{t \rightarrow \infty} x^t = \mathbf{x}^*\right) \geq \left(1 - \frac{2}{kN^\tau}\right) e^{-k/N^\tau}.$$

Theorem 2 gives a quantitative explanation of the “mass inertia” principle described previously. If, at the τ th round of adoption, the market share is close to a stable equilibrium \mathbf{x}^* , nothing rules out the stochastic process of adoption jumping to another basin of attraction.¹² However, the larger N^τ , the cumulative number of subscribers at time τ , the smaller the probability of such a jump.

III. Equilibria

To identify the standard(s) that may emerge as the long-run outcome of the stochastic process of adjustment, by virtue of Theorem 1 we need only study the fixed points of P . Our candidates for equilibrium are the solutions of: $P_A(x, 1 - x) = x$ [or, equivalently, $P_B(x, 1 - x) = 1 - x$]. From equation (3) we derive:

$$(8) \quad x = F\left(\frac{u_A(x)}{u_A(x) + u_B(1 - x)}\right).$$

The candidates for long-run equilibrium are the pure-strategy equilibria of a static coordination game. In a game where everybody

⁹ Figure 5a shows the stochastic market-share evolution of standard A for an initial number of adopters $N_A^0 = 1$ and $N_B^0 = 20$ and utility functions $u_A(x) = (1 + x)^{1.5} - 1$ and $u_B(y) = y^2$. The final number of adoptions is 150,021. The time scale is $\ln(t + 21)$ where t is the number of adoptions.

¹⁰ We are grateful to an anonymous referee for pointing out this fact. For more on replicator dynamics, see Jorgen W. Weibull (1995) and Fudenberg and Levine (1998).

¹¹ We are grateful to an anonymous referee for suggesting this discussion on stability.

¹² Indeed, according to assertion (ii) of Theorem 1, this event has a positive probability of occurrence.

adopts simultaneously, an outcome is said to be an equilibrium if no individual “would wish to defect to a different specification of the good from the one he is meant to be getting, on the (equilibrium) assumption that he would be the only defector” (Farrell and Saloner, 1986). It is easy to check that the pure-strategy equilibria of the static game constitute solutions to equation (8). In particular, $P_A(1, 0) = 1$ (standardization on A) and $P_A(0, 1) = 0$ (standardization on B) are always equilibria. Moreover, depending on functions u_A , u_B , and F , incompatibility solutions also exist. For the purpose of analyzing these, we assume, in what follows, that the agents are uniformly distributed over $[0, 1]$.

ASSUMPTION 2': δ is uniformly distributed over $[0, 1]$.

This implies that each type of agent is equally likely to enter the market. Under Assumption 2', equation (8) simply becomes: $(1 - x)u_A(x) = xu_B(1 - x)$. This allows us to concentrate on the impact of individuals' preferences, represented by u_A and u_B , on standardization. In the spirit of the literature on uncertainty, we introduce the definitions of tolerance and aversion to incompatibility.

Definition 1: After selecting either standard A or B , consider the choice between being matched with a population where either (i) with probability μ everybody uses standard A and with probability $(1 - \mu)$ everybody uses standard B ; or (ii) μ percent of the population uses standard A and $(1 - \mu)$ percent uses standard B . An attitude toward standardization is said to be “incompatibility-averse” if it leads to a strict preference for (i). It is said to be “incompatibility-tolerant” if it leads to a strict preference for (ii). It is said to be “incompatibility-neutral” otherwise.

The way coordination externalities shape preferences depends on how and why individuals coordinate. For instance, if, after choosing a vehicle with a left- or right-hand drive, the choice is to be sent to a city where either (i) with probability $1/2$ everybody drives on the left-

hand side of the road and with probability $1/2$ everybody drives on the right-hand side of the road, or (ii) half the people drive on the left-hand side and the other half on the right-hand side, everybody would choose (i). On the other hand, when a similar choice involves desktop-computer technology with Macintosh versus an IBM-compatible format, a majority of people choose (ii). Clearly, individuals' attitudes toward incompatibility depend on the nature of the standard at stake.

Where coordination failures are very costly to users, their attitude toward standardization will be incompatibility-averse. This occurs if imperfect standardization puts them at risk, as is the case with air, sea, or road traffic regulations and signs, fire or electrical norms, and drug or chemical formulas. The great Baltimore fire of 1842 provides a good illustration of this. As Samuel Krislov (1997) recalls, “Fire departments from the general area rushed to help and had to stand helplessly by since the couplings for their water hoses were incompatible with local designs.” Typically, this is a case where standardization, even on an inferior hose design, would have been better than incompatibility. The loss of the Titanic in 1912 gives another example. The liner Californian was only a few miles away and hundreds of lives could have been saved had it picked up the Titanic's SOS call. At the first International Convention for Safety of Life at Sea (SOLAS) in London 1914, it was decided that large vessels should maintain 24-hour radio watch. This rule has remained in force ever since.

By contrast, individuals' attitudes toward incompatibility will be tolerant when coordination failures cost them little. This occurs if benefits associated with a new adoption stagnate with a high number of adoptions. Examples include the video recorder, CD player, or personal computer. When the number of complementary goods (i.e., videos, CDs, or software) is large, users do not benefit from further new adoptions. From their point of view, the gains of coordination being indirect, there are decreasing returns to scale in adoption. Finally, individuals' attitudes toward incompatibility will be neutral when the marginal benefit associated with a new adoption, for a fixed population, is constant. This is the case with telephone, facsimile, or computer

networks because for one-to-one communication each subscriber is equally important. For equipment providing a direct communication service, there are constant returns to scale in adoption which characterizes neutrality.

The different attitudes toward incompatibility shape the individuals' utility functions. Tolerance to incompatibility leads, by virtue of Definition 1, to the strict choice of (ii). This is equivalent to $\mu_k u_k(1) + (1 - \mu_k)u_k(0) < u_k(\mu_k) \forall \mu_k \in (0, 1)$. A sufficient condition for this inequality to be true for all $\mu_k \in (0, 1)$ is the strict concavity of u_k . In other words, concavity of u_k indicates tolerance to incompatibility. Similarly, convexity of u_k indicates aversion to incompatibility. Indeed, the strict convexity of u_k implies $\mu_k u_k(1) + (1 - \mu_k)u_k(0) > u_k(\mu_k) \forall \mu_k \in (0, 1)$, which leads to the strict choice of (i). Finally, neutrality to incompatibility, which leads to indifference, is equivalent to linearity: $\mu_k u_k(1) + (1 - \mu_k)u_k(0) = u_k(\mu_k) \forall \mu_k \in (0, 1)$. In what follows, we distinguish two cases: both $u_A(\cdot)$ and $u_B(\cdot)$ are convex or linear; both $u_A(\cdot)$ and $u_B(\cdot)$ are strictly concave. As will be shown, this difference matters.

A. Aversion and Neutrality to Incompatibility

First of all, consider the case where the utility functions are linear, that is $u_A(x) = ax$, $u_B(x) = bx$, and are equal to each other, $a = b$. This implies in equation (3) $P_A(x, 1 - x) = x \forall x \in [0, 1]$: Any market-share allocation $x \in [0, 1]$ is a stable equilibrium of the ODE (7) and, by virtue of Theorem 1, a potential candidate for market equilibrium. When individuals display neutrality to incompatibility and the standards are a perfect substitute, the problem is degenerated. In what follows, we rule out this case on the ground that it is nongeneric. In practice there are always differences between standards. Yet if a and b are very close, but are not exactly equal to each other, the equilibrium is uniquely determined.¹³ In the linear case, we pose:

ASSUMPTION 3: $a \neq b$.

When utility functions are convex, or linear, with respect to market share, the marginal

benefit associated with new adoptions increases with the number of adopters. The benefits individuals derive from standardization are large. It is intuitive that they would exceed the gains from diversity associated with an incompatibility equilibrium and eventually drive the decentralized adjustment process toward standardization.

PROPOSITION 1: *When utility functions are convex, or linear, standardization occurs with probability one. Nevertheless, the selected standard is not always predictable. It is*

either A or B if:

$$u'_A(0) \leq u_B(1) \text{ and } u'_B(0) \leq u_A(1) \quad (\text{AN1})$$

$$A \text{ if: } u'_A(0) > u_B(1) \quad (\text{AN2})$$

$$B \text{ if: } u'_B(0) > u_A(1). \quad (\text{AN3})$$

PROOF:

See Appendix A.

When individuals display aversion or neutrality to incompatibility, there is a corner solution. The positive coordination externalities are strong enough to push the decentralized adoption process toward standardization. The standard selected depends on the conditions illustrated in Figure 1.

The interpretation of these conditions is as follows. Condition (AN1) implies that the utility associated with the adoption of standard A is, for identical market shares, similar to the utility associated with the adoption of standard B. That is to say, $u_A(x)$ and $u_B(x)$ are not too different. When neither standard is significantly better than the other, knowledge of adopters' behavior and the characteristics of the standards are not sufficient to predict equilibrium. Depending on initial conditions and the actual play of the first rounds of adoption, either technology may end up as a de facto standard. This situation corresponds to the case described by Arthur (1988, 1989). Increasing or constant returns exacerbate "historical events," so that, if, by chance, one of the standards has gained an adoption advantage, it increases its lead

¹³ Standardization occurs on A if $a > b$, and on B if $a < b$.

¹⁴ When $a = b$, depending on "historical events," any market-share allocation may end up as the equilibrium.

and eventually conquers the whole market. An extreme example of path-dependency, which is ruled out by Assumption 3, is provided by the linear case; (AN1) is equivalent to $a = b$.¹⁴ For a nice illustration of the path-dependent and lock-in properties, see the explanation by Paul A. David (1985) of how the QWERTY typewriter keyboard arrangement ended up as the U.S. national standard.

On the other hand, condition (AN2) implies that, for identical market share, the gross utility derived from the adoption of standard A is always higher than that derived from the adoption of standard B [and vice versa under condition (AN3)].¹⁵ For instance, in the linear case, (AN2) is equivalent to $a > b$ and (AN3) to $b > a$. We then say that standard A has a *pronounced* advantage over standard B (respectively standard B over standard A), in the sense that it is sufficiently better to drive its competitor out of the market independently of initial conditions (N_A^0, N_B^0). In the telecommunications industry, an example of such a pronounced advantage is given by the telephone as compared to the telegraph.

Figure 2 describes the probability, under the convexity assumption, that the next adopter will choose standard A as a function of the current market share x_A (the probability of choosing B as a function of B's market share is the complement in the unit square). The candidates for equilibrium (i.e., the fixed points of P) are the intersection points of function P_A and the bisectrix. Convergence to equilibria (stable fixed points) is indicated by the arrows.

B. Tolerance to Incompatibility

When the utility functions are concave in market share, there are, from the individuals' points of view, decreasing returns to adoption. The marginal benefit associated with a new adoption, for a fixed population, decreases with

¹⁵ Since the utility functions are rising and convex, (AN2) [respectively (AN3)] implies that the line connecting (0, 0) to (1, $u'_A(0)$) [respectively (0, 0) to (1, $u'_B(0)$)] is always below the curve $u_A(x)$ [respectively $u_B(x)$]; see Figure 1. Moreover, since $u_B(1) \geq u_B(x) \forall x \in [0, 1]$, (AN2) [respectively (AN3)] implies that $u_A(x) > u_B(x) \forall x \in (0, 1]$ [respectively $u_B(x) > u_A(x)$].

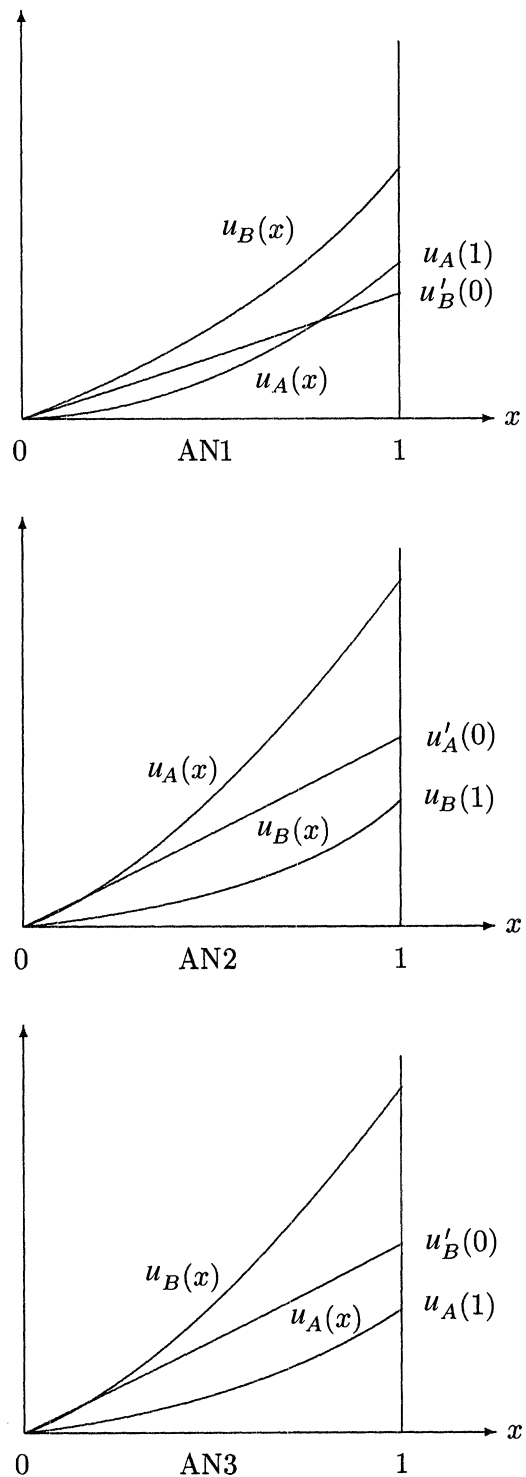


FIGURE 1. THE CONVEX CASE

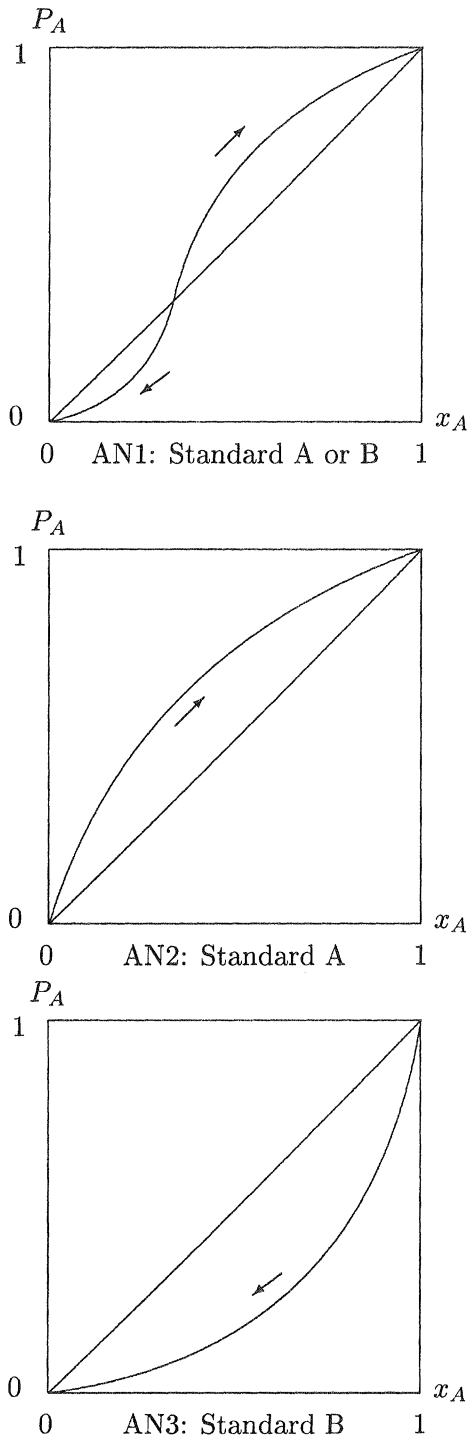


FIGURE 2. EQUILIBRIA
THE CONVEX CASE

the number of adopters. Coordination failure being less costly to users, it comes as no surprise that incompatibility solutions occur.

PROPOSITION 2: *When the utility functions are strictly concave, market share is always predictable. Standardization, however, is no longer systematic. The market*

sustains incompatibility if:

$$u'_A(0) \geq u_B(1) \text{ and } u'_B(0) \geq u_A(1) \quad (T1)$$

$$\text{standardizes on A if: } u'_B(0) < u_A(1) \quad (T2)$$

$$\text{standardizes on B if: } u'_A(0) < u_B(1). \quad (T3)$$

PROOF:

See Appendix A.

Under tolerance to incompatibility, the decentralized process of adoption is always predictable. That is, concavity cushions coordination externalities and eliminates historical events, so that, given initial conditions N_A^0 and N_B^0 , the outcome is known. Figure 3 illustrates that the actual outcome differs as a function of the conditions.

The interpretation of these conditions is as follows. Conditions (T2) and (T3) are equivalent to conditions (AN2) and (AN3). When either competitor has a pronounced advantage over its competitor, it eventually drives the latter out of the market and becomes the unique standard [condition (T2) corresponds to a pronounced advantage of standard A over standard B, and conversely for condition (T3)]. In the recording industry, an example of such pronounced advantage is given by the CD as compared to vinyl.

On the other hand, under condition (T1), which is similar to condition (AN1), utility functions $u_A(x)$ and $u_B(x)$ are not too different. When neither standard is significantly better than the other, individuals prefer to not coordinate on a single standard rather than give up their personal preferences. Examples of such incompatibility solutions include the coexistence of Nintendo and Sega video games, Macintosh and IBM-compatible PC technology, and CD and cassette-tape players. An indication of tolerance to incompatibility is that incompatible standards may exist side by side for long periods. Figure 4 illustrates the three different

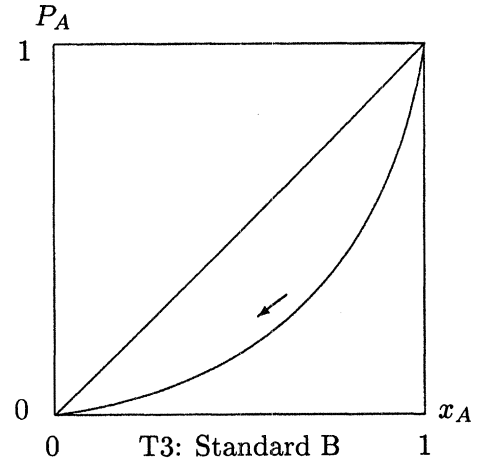
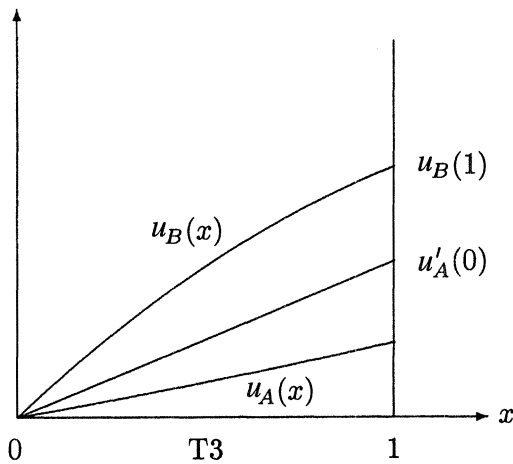
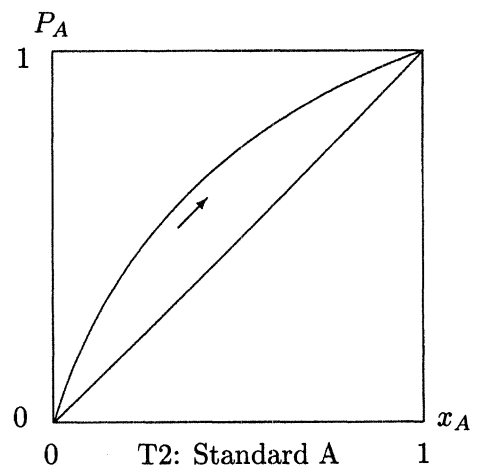
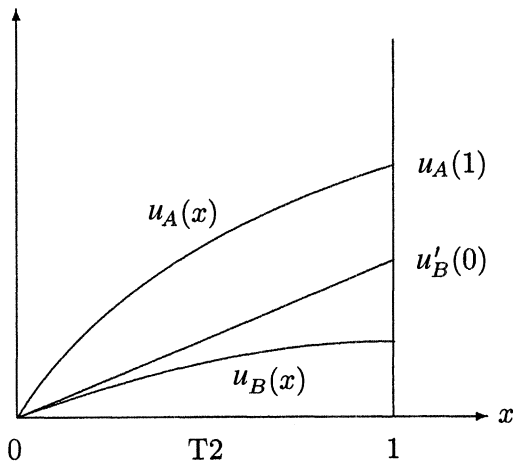
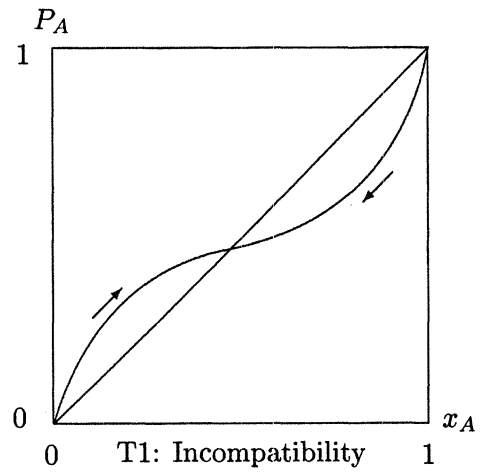
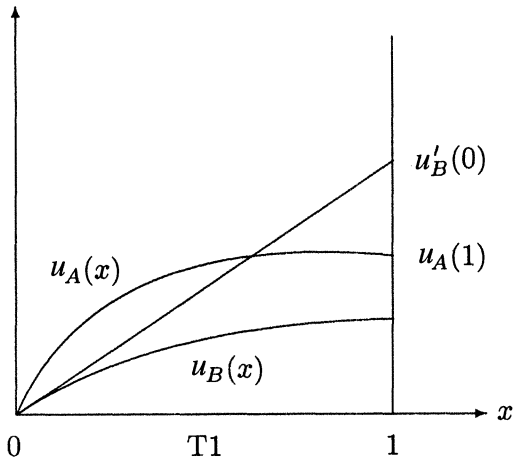


FIGURE 3. THE CONCAVE CASE

FIGURE 4. EQUILIBRIA
THE CONCAVE CASE

cases. It describes the probability that the next adopter will choose standard A as a function of A 's current market share. Stable equilibria are indicated by the arrows.

C. Diffusion Curves

There is not much hard evidence on standardization. The major part of the literature is micro-oriented and qualitative in nature. An exception is found in the literature on diffusion curves for new technologies. When a new technology is introduced, it may or may not succeed in achieving a stable market share. However, when it does so, market-share evolution across time is known to follow an S-shaped curve (see, for instance, Lars Nasbeth and George-Frank Ray [1974] or Stephen Davies [1979]). That is, the proportion of adoption across time is an increasing function which is at first convex and subsequently concave. In the telecommunication industry, the inflection point is often referred to as the "critical mass" point. Telex (see Luis M. B. Cabral and Antonio P. N. Leite [1992] for Portugal) and telephone diffusion curves (see Koichiro Hayashi [1992] for Japan) have behaved in this way. Since observed diffusion curves are S-shaped independently of the technology or commodity at stake, we need to compare the results of our paper with this empirical fact. With this in mind, we consider the case in which a new standard or innovation is good enough to win a stable share of the market. We compute the diffusion curve (the evolution of market share across time), in association with the deterministic system that drives the dynamic process.

PROPOSITION 3: *Diffusion curves associated with the deterministic system (7) are S-shaped independently of individuals' attitudes to incompatibility.*

PROOF:

See Appendix B.

The problem with Proposition 3 is that it is established for the associated deterministic system defined by equation (7), which describes the dynamics of the process in the long run (i.e., when the cumulated number of adopters is large). A priori it says nothing about the diffusion curves of the true stochastic process that

characterizes the dynamics of adoption of a new standard. The relevance of Proposition 3 depends on how quickly the shape of the stochastic process defined by (5) comes to resemble the deterministic process (7).

Given an initial market share x_0 , let $\{x(t)\}_{t \geq 0}$ denote the deterministic solution to (7) with initial condition $x(0) = x_0$ and let $\{x^t\}_{t=0,1,\dots}$ denote the stochastic sequence of market shares given by (5) with the same initial condition. For each integer $t \geq 1$ define the new time scale

$$\tau_t = 1 + \frac{1}{2} + \dots + \frac{1}{t}.$$

The next theorem, which follows from Benaim (1999 Sec. 4.2), establishes that the higher the N^0 , the initial number of adopters of the old standard, the higher the probability that the diffusion curves will be S-shaped.

THEOREM 3: *There exist positive constants c_1 and c_2 (depending only on u_A and u_B) such that: For each $\alpha \geq 0$ and every $T > 0$*

$$\begin{aligned} & \text{Prob} \left(\sup_{t:0 \leq \tau_t \leq T} \|x^t - x(\tau_t)\| \geq \alpha \right) \\ & \leq \exp \left(-N^0 \frac{\alpha^2}{2c_1 T} + c_2 T \right). \end{aligned}$$

In other words, Theorem 3 establishes that the stochastic process remains close to the deterministic path $x(\tau_t)$ with high probability over finite but arbitrarily large time intervals, provided the initial number of adopters N_0 is large enough. Therefore, the larger the N_0 , the greater is the probability of being able to observe an S-shaped diffusion curve for the stochastic adoption process. Such behavior is observed in several numerical simulations depicted in Figure 5 (Panels a, b, c, d). By convention the "old" standard is B , the new one is A . The depicted market share is x_A . The time scale is $\ln(t)$.¹⁶ The aggregated collec-

¹⁶ $\tau_t = 1 + 1/2 + \dots + 1/t$ is converging to $\ln(t)$.

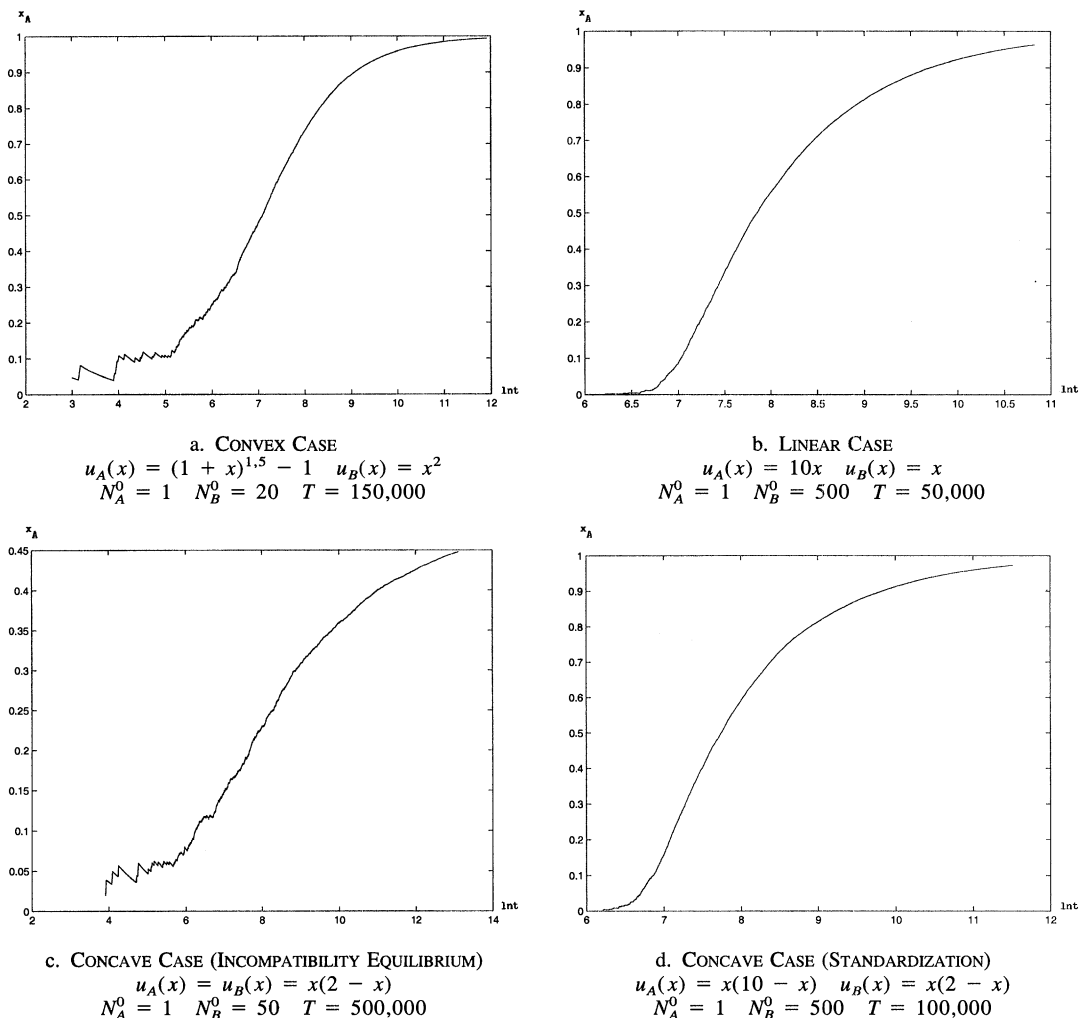


FIGURE 5. DIFFUSION CURVES

tive behavior generated by theoretical analysis is consistent with the empirical evidences on diffusion curves.

IV. Welfare Analysis

As mentioned in the introduction, there is growing concern worldwide over standardization issues. Two lines of conduct emerge: the “regulated way,” which tends to favor a centralized approach to the setting of standards, and the “decentralized way,” which tends to rely on market forces. Since nonharmonized

standards are technical barriers to trade, the EU favors the centralized way. Standardization in the EU is mandatory by law.¹⁷ This is

¹⁷ The European Committee for Standardization (ECS) publishes European Standards, which are adopted after a vote where 71 percent or more of the expressed votes are in favor. In contrast to other institutions, in particular the International Organization for Standardization (ISO), countries voting against are still obliged to implement European Standards by giving them the status of national standard (for more on ISO, and for links to ECS and other standardization organizations, see the ISO homepage: www.iso.ch [1999]).

in contrast with the United States, which favors a decentralized approach that relies on “voluntary” standardization. The question we address next is whether there is a need for centralized intervention at all.

We compute the socially optimal market-share allocation and contrast this with the decentralized equilibrium. Assuming each individual is given the same weight, the long-run optimal market-share allocation maximizes consumers’ average utility. For given market shares $x = (x_A, x_B)$, this average utility is:

$$W(x_A, x_B) = \int_0^{\delta_L} (1 - \delta) u_A(x_A) d\delta + \int_{\delta_L}^1 \delta u_B(x_B) d\delta.$$

Integrating this expression, the long-run optimal market-share allocation is the solution of:

$$(9) \quad \begin{aligned} \text{Max}_x W(x_A, x_B) \\ &= \frac{u_A(x_A) + u_B(x_B)}{2} \\ &\quad - \frac{u_A(x_A)u_B(x_B)}{2[u_A(x_A) + u_B(x_B)]}. \end{aligned}$$

A. Aversion and Neutrality to Incompatibility

It is easy to check that utility-function convexity implies the strict convexity of $W(x_A, x_B) = W(x_A, 1 - x_A)$ in x_A . When individuals display either aversion or neutrality to incompatibility, the optimum is a corner solution: $x_A^* = 1$ or $x_A^* = 0$.

PROPOSITION 4: *When utility functions are convex or possibly linear, it is always optimal to standardize. If $u_A(1) > u_B(1)$, it is optimal to standardize on A, and, otherwise, on B.*¹⁸

¹⁸ It might be the case that $u_A(1) = u_B(1)$. The optimum is then standardization on either A or B.

This result is intuitive. Where individuals display either aversion or neutrality to incompatibility, the social gains derived from standardization on the dominant standard are very strong. Such gains overwhelm the potential diversity benefit associated with an incompatibility solution. We compare the decentralized outcome with the socially optimal solution.

COROLLARY 1: *Under neutrality to incompatibility, the decentralized standardization process always leads to an efficient outcome. By contrast, under aversion to incompatibility, the decentralized outcome is not necessarily an optimum. It is optimal when condition (AN2) or (AN3) holds, but may be inefficient otherwise.*

This result is straightforward. Under neutrality to incompatibility, individuals always manage to standardize on the dominant technology. By virtue of Proposition 4, this is optimal. Under aversion to incompatibility, individuals always manage to standardize. So, when one standard performs clearly better than another one, they are able to coordinate on the superior standard. However, when the standards are not sufficiently different, as under (AN1), they sometimes pick the inferior one. Once this happens, it is very difficult to backpedal or switch to the superior variant. Indeed, by virtue of Theorem 2, the probability of switching, from a standard with “installed base” N to a standard without installed base, is proportional to $1/N$. The higher N , the lower the probability of a switch. This is illustrated by the history of the U.S. keyboard format. All attempts made to switch from the QWERTY format to the alleged superior DVORAK one have failed (see David, 1985, and discussion by Liebowitz and Margolis, 1994).

B. Tolerance to Incompatibility

When the utility functions are strictly concave, the results are more ambiguous. No matter how great the degree of individuals’ tolerance to incompatibility (no matter how great the concavity of their utility functions), aggregate welfare itself cannot be concave. The presence of positive coordination externalities tends to convexify the problem and

push the solution into the corners. So, under the following condition, which requires that the function u_A and u_B are weakly concave, the maximization problem is convex. There is a corner solution.¹⁹

$$(T4) \quad -u''_A u_A - u''_B u_B \leq (u'_A P_B + u'_B P_A)^2.$$

Similarly, when one standard is totally dominated by the other (i.e., is obsolete), there is also a corner solution. Actual obsolescence is defined in the following terms.²⁰

$$(T2+) \quad u'_A(1) > u'_B(0)$$

$$(T3+) \quad u'_B(1) > u'_A(0).$$

However, as stated in the following proposition, the optimal trade-off between diversity and compatibility does not always lead to standardization on the dominant standard.

PROPOSITION 5: *In the concave case when either condition (T2+), (T3+), or (T4) is satisfied, standardization on the dominant standard, $\operatorname{argmax}\{u_A(1), u_B(1)\}$, is optimal. An incompatibility solution might dominate standardization otherwise.*

PROOF:

See Appendix C.

Concavity cushions coordination externali-

¹⁹ Condition (T4) requires that the second derivatives (left term) are not too big compared to the first derivatives (right term). The linear case, which is both convex and concave, is an extreme example of weak concavity which fits with condition (T4). An example of strictly concave functions satisfying Assumption 1 and condition (T4) is: $u_A(x) = 20x - x^2$ and $u_B(y) = 0.5(20y - y^2)$.

²⁰ The concavity of the utility functions implies that the slope of $u_k(x)$ is always smaller than the slope of the line connecting $(0, u_k(0))$ to $(x, u_k(x))$, that is $u'_k(x) \leq u_k(x)/x \forall x \in (0, 1]$ ($k = A, B$). This implies $u'_A(1) \leq u_A(1)$ and $u'_B(1) \leq u_B(1)$ such that $u'_A(1) > u'_B(0) \Rightarrow u_A(1) > u'_B(0)$ and $u'_B(1) > u'_A(0) \Rightarrow u_B(1) > u'_A(0)$. Condition (T2+) [respectively (T3+)] is stronger than condition (T2) [respectively (T3)]. They are equivalent in the linear case.

ties so that an incompatibility solution is sometimes preferable to full-blown standardization. This occurs when the benefits of adoption run out with a large number of adopters.²¹ Standardization deprives consumers of valuable diversity without providing corresponding compatibility benefits. We next compare the optimal solution with the decentralized outcome.

COROLLARY 2: *Under tolerance to incompatibility, the decentralized outcome is optimal when one standard is obsolete with respect to the other, or when one standard has a pronounced advantage over the other, and, simultaneously, utility functions are weakly concave. The outcome may not be efficient otherwise.*

PROOF:

See Appendix D.

When standards are not significantly different [i.e., under condition (T1)], the market sustains an incompatibility equilibrium, but it is easy to find cases where it would be better to standardize. Similarly, when one standard has a pronounced advantage over the other [i.e., under (T2) or (T3), but not (T2+) or (T3+)], the market always standardizes, even if, in some cases, an incompatibility solution would be better for society as a whole. An insufficient degree of standardization or excessive degree of standardization illustrates the same problem. In the presence of tolerance to incompatibility, the decentralized adoption process tends to overlook small groups of users and to favor large ones in their respective need for diversity.

C. Regulation vs. Laissez-Faire

The inefficiencies involved in laissez-faire are not surprising: we are dealing with externalities. The question these inefficiencies raise, however, is whether regulation should

²¹ For instance, if the utility functions increase to a certain market-share ceiling and then stagnate, even with one standard inferior to the other [e.g., under (T2) but not $u'_A(1) > u'_B(0)$], standardization is suboptimal.

be preferred to the decentralized process. This is a delicate question because for planners to make the optimal decision requires not only that they have a comprehensive knowledge of individuals' preferences but also that they be benevolent. Especially in decentralized economies, information is widely dispersed. Users are the only ones to know their own preferences and needs. Moreover, people are generally self-interested and opportunistic. Institutions' attempts to assert their own authority in standardization issues in the United States illustrates this opportunism problem. Most emanate from industry representatives who try to stall competition through the "official standards" they promote. The proliferation of these organizations, which have been called a "maze," creates a crowding-out effect. It is then left to the market to achieve standardization.

In the case of neutrality and tolerance to incompatibility, this might be a good thing, because users take time to experiment. For instance, personal-computer technology was introduced in 1977 and is still not completely standardized 20 years later. The risk of "lock-in" is irrelevant. In fact, people have been able to make the switch from traditional typewriter to computer, from vinyl-record player to compact-disk player, and from telegraph to telephone. This is in contrast with the risk of regulators or experts misrepresenting consumer tastes and needs. For instance, Nathan Rosenberg (1993) recalls that "Western Union was given the opportunity to purchase Bell's telephone patent in 1877 for \$100,000, but turned it down." Similarly "Marconi's invention of the 'wireless' was originally perceived as a technology for ship-to-shore communication." These examples concerning telephones and radio illustrate the fact that contemporaries were unable to foresee the future use to which these innovations would be put. Since it is difficult to forecast which innovations will be successful and which will not, the issue of experimentation by users is very important. The experience of the European Committee for Standardization confirms that early attempts to standardize new technologies are counterproductive. Standards that took several months to emerge were generally obsolete before their publication. The ECS has thus changed its strategy. It is now

favoring a "performance" approach to standardization; it promotes minimal standards for quality and safety rather than complete commodity design.

Whenever safety issues are at stake, thoughtful and concerted action is necessary to hasten the standardization process and orient it to the best alternative. For instance, the first international standardization organization was the International Electrotechnical Commission. Created in 1906, it gave rise to the first coherent grids that turned electricity into a safer and more reliable source of energy. This was necessary to convince reluctant consumers to adopt it.

In our own day, the problem of illegal drugs illustrates our point. A recent study from the National Center for Health Statistics revealed that 80 percent of poisoning-injury deaths in the United States are drugs related. "Opiates and cocaine were two of the leading causes of drug-related poisoning death" (May/June 1998 issue of *Public Health Report*). Since these drugs are illegal, their composition fails to meet safety standards, which explains many poisonings. Similarly, in developing countries the proliferation of counterfeit drugs, which vary in their composition from one dealer to the other, constitutes such a threat to health that a vast majority of the inhabitants prefers to avoid them.²² For instance, a survey in Zimbabwe suggests that 80 percent of the population relies on traditional remedies because people are too poor to buy official medicines and those available on the street are very unreliable. These problems arise because "many developing countries lack national standards that are compatible with the international norms developed by such bodies as ISO. Moreover, the national institutions responsible for developing standards and assessing conformity are often weak" (World Bank, 1998). Without a minimal level of coercive standardization, in particular quality and safety performance standards, complex decentralized systems cannot operate. Standard setting is at the core of nation building and a keystone of economic integration.

²² A study in Nigeria concluded that up to 60 percent of medicines on the street market were counterfeit.

V. Conclusion

This paper offers an insight into how standards and norms emerge in decentralized economies. In particular, it provides a way to link individuals' attitudes toward incompatibility with the collective outcome of the standardization process. When individuals display aversion to incompatibility, standardization is systematic. Still, the actual standard which will be selected is not always predictable. Dispersed individuals sometimes make mistakes and pick the dominated standard. On the other hand, when individuals display tolerance to incompatibility, the decentralized process of adoption is always predictable, but it may sustain an incompatibility equilibrium and usually fails to achieve the optimal trade-off between compatibility and diversity. However, if standardization occurs, it is always on the best alternative. Finally, when individuals display neutrality to incompatibility, standardization on the dominant standard is systematic. Consistent with the empirical evidence, our analysis yields an aggregated collective behavior which generates S-shaped diffusion curves.

Contrary to what was suggested by Arthur's (1988) seminal work, path-dependency is not a central feature of standardization in decentralized economies. The decentralized process of adoption is predictable, except for standards that are subject to aversion to incompatibility and are not significantly different from each other. Overall predictability in this context means that, somehow, negligible and anonymous agents are able to coordinate. This is consistent with evolutionary game-theory results. Successive myopic adoptions give rise to some kind of unconscious collective maximizing behavior. The emergence of this structure of collective behavior is very interesting because it is not driven by any single conscious will. It is a social phenomenon. We conclude that centralized intervention is necessary when individuals display aversion to incompatibility. In this case, coordination failures are costly to users, so that it is a priority to achieve rapid, well-thought-out standardization. On the other hand, in cases of tolerance or neutrality to incompatibility, individuals take time to experiment and never end up mistaking a bad standard for good one. Gam-

bling on the choice of a standard, for the sake of achieving early standardization, is unlikely to improve welfare. Where there is no imperative coordination problem and in the absence of safety concerns, it seems better to rely on decentralization.

As a further extension of this study, the effect on standardization of other population probability distributions could be analyzed. It could also be extended to studying the case of competition between incompatible standards in the presence of a larger number of standards.

APPENDIX A: PROOF OF PROPOSITIONS 1 AND 2

Equilibrium Candidates.—Under Assumption 1, both $x_A = 1$ and $x_A = 0$ are solutions to equation (8). An interior solution also exists if and only if it exists $x \in (0, 1)$ such that
$$H(x) = \frac{u_A(x)}{x} - \frac{u_B(1-x)}{1-x} = 0.$$
 Since $H(x)$ is increasing when $u_A(x)$ and $u_B(y)$ are convex and is decreasing when they are concave, this is equivalent to $\lim_{x \rightarrow 0} H(x) = u'_A(0) - u_B(1)$ and $\lim_{x \rightarrow 1} H(x) = u_A(1) - u'_B(0)$ having opposite signs. In the linear case, $H(x) = a - b$, and it exists an (infinity of) interior solution if and only if $a = b$, which is ruled out by Assumption 3. We easily deduce conditions (AN1) and (T1), which we complete by conditions (AN2) and (AN3), and (T2) and (T3), respectively.

Stability.—In this one-dimensional setting, an equilibrium is locally stable (respectively unstable) if the derivative of the function
$$G(x) = \frac{u_A(x)}{u_A(x) + u_B(1-x)} - x$$
 taken at the equilibrium point is negative (respectively positive). That is, an equilibrium x_A^* is locally stable (respectively unstable) if, at $x_A = x_A^*$, $P'_A - 1 < 0$ (respectively $P'_A - 1 > 0$). It is easy to check that the equilibrium $x_A^* = 0$ is stable under conditions (AN1) and (AN3) and under condition (T2), but unstable under condition (AN2) and under conditions (T1) and (T3). Similarly, it is easy to check that the equilibrium $x_A^* = 1$ is stable under conditions (AN1) and (AN2) and under condition (T3), but unstable under condition (AN3) and under conditions (T1) and (T2). For the interior equilibrium $x_A^* =$

$x^l \in (0, 1)$ ($x_B^* = 1 - x^l$), which exists only under condition (AN1) or (T1), we have

$$G'(x)|_{x=x^l} = x^l \frac{(1-x^l)u'_A(x^l) + x^l u'_B(1-x^l)}{u_A(x^l)}$$

– 1. We get $G'(x)|_{x=x^l} \geq 0$ under condition (AN1), and $G'(x)|_{x=x^l} \leq 0$ under condition (T1). The interior equilibrium is unstable under condition (AN1), and stable under condition (T1). These results are illustrated in Figures 2 and 5 (when the probability function has a positive slope at the equilibrium point, the equilibrium is unstable; it is stable otherwise).

APPENDIX B: PROPOSITION 3 (DIFFUSION CURVES)

Let standard A be an innovation so that in the convex case condition (AN2) holds, and in the concave case either condition (T1) or (T2) holds. Let x_A^* denote the market share that standard A wins at equilibrium [i.e., $x_A^* = 1$ under (AN2) and (T2), $x_A^* \in (0, 1)$ under (T1)]. Let $x(t)$ denote the diffusion curve—the market-share evolution across time—of standard A. From basically zero at its introduction time, $x(t)$ is going to rise across time and eventually converge to $x_A^* > 0$. Since under (AN2) [respectively (T1) and (T2)], P_A is always greater than x for all $0 < x \leq x_A^*$ (see Figures 2 and 4), we deduce from equation (7) that $x'(t) = P_A(x, 1 - x) - x > 0$. The diffusion curve, $x(t)$, is increasing.

We study next its shape. It is given by:

$$x''(t) = x'(t) \left(\frac{dP_A(x, 1-x)}{dx} - 1 \right).$$

Since $x'(t) > 0$, the convexity/concavity of the diffusion curve depends on the sign of $\frac{dP_A(x, 1-x)}{dx} - 1 \forall x \leq x_A^*$. Under (AN2)

[respectively (T1) and (T2)], there exists an inflection point, \hat{t} , for $x(t)$. It is reached when $\frac{dP_A(x, 1-x)}{dx} = 1$. Let $\hat{x} = x(\hat{t})$ be the image of \hat{t} . It is the point where P_A parallels the bisectrix, so that $\hat{x} = x(\hat{t}) \in (0, x_A^*)$. We deduce that $x''(t) > 0$ for $t < \hat{t}$, and $x''(t) < 0$ for $t > \hat{t}$, showing that the function, $t \rightarrow x(t)$, is S-shaped. This is illustrated in Figure 5.

APPENDIX C: PROOF OF PROPOSITION 4

Under condition (T2+) [respectively (T3+)], the function $\frac{u_A(x_A) + u_B(1-x_A)}{2}$ is increasing in x_A (respectively decreasing). It is thus maximum for $x_A = 1$ (respectively $x_A = 0$). Since $W(x_A, 1-x_A) < \frac{u_A(x_A) + u_B(1-x_A)}{2}$ for all $x_A \in (0, 1)$, and $W(x_A, 1-x_A) = \frac{u_A(x_A) + u_B(1-x_A)}{2}$ for $x_A = 0$ or $x_A = 1$, the optimum is a corner solution: $x_A^* = 1$ under (T2+), and $x_A^* = 0$ under (T3+). When u_A and u_B are concave, $W(x_A, 1-x_A)$ cannot be concave. Indeed $\frac{dW}{dx_A} \Big|_0 = \frac{-u'_B(1)}{2} <$

$0 < \frac{dW}{dx_A} \Big|_1 = \frac{u'_A(1)}{2}$, where the concavity requires

$\frac{dW}{dx_A}$ to be decreasing. It can however be convex. Let $\frac{d^2W}{dx_A^2} = \frac{\left[\frac{u''_A u_A + u''_B u_B}{(u_A + u_B)} + \frac{(u'_A u_B + u'_B u_A)^2}{(u_A + u_B)^3} \right] - \frac{u''_A u_A^3 + u''_B u_B^3 + u_B u_A (u''_A u_A + u''_B u_B)}{2(u_A + u_B)^3}}$. Condition

(T4) and $u''_k \leq 0$ imply that $\frac{d^2W}{dx_A^2} \geq 0$. The optimum

is a corner solution: $x_A^* = 1$ or $x_A^* = 0$. When condition (T4) is not satisfied, the social welfare function can be neither convex nor concave (the problem does not admit a general analytical solution). It is then possible to find cases where standardization is no longer optimal. For instance, let $u_A(x) = u_B(x) = Kx - x^2$, $K > 2$. It is easy to check that $W(1/2, 1/2) = \frac{3}{8}(K - 0.5) > W(0, 1) = W(1, 0) = \frac{1}{2}(K - 1)$ for $K < 2.5$. An incompatibility solution dominates standardization when $K \in (2, 2.5)$.

APPENDIX D: PROOF OF COROLLARY 2

Since condition (T2+) [respectively (T3+)] implies condition (T2) [respectively (T3)], when (T2+) or (T3+) is satisfied, the market outcome (standardization) is efficient. Similarly, since under condition (T4) it is optimal to standardize, when (T4) holds with either (T2) or (T3) the market outcome is also efficient. How-

ever, when none of these conditions hold, the market outcome can be inefficient.

For instance, let $u_A(x) = u_B(x) = Kx - x^2$, $K > 2$. It is easy to check that, under this specification, condition (T1) is satisfied so that the market is going to sustain the incompatibility equilibrium: $x_A^* = 1/2$, $x_B^* = 1/2$. But if simultaneously $K \geq 2 + \sqrt{2}$, condition (T4) holds so that it would be socially optimal to standardize [since the left side of the inequality in (T4) is minimum for $x_k = 1/2$, a sufficient condition for (T4) is $u'(1/2) = K - 1 \geq [2x(K - x) + 2(1 - x)(K - 1 + x)]^{0.5}$ which is true as soon as $K \geq 2 + \sqrt{2}$]. More surprisingly the market can standardize when it would be optimal to sustain diversity. Let $u_A(x) = u(x)$ and $u_B(x) = \beta u(x)$ with $u(x) = \int_0^x v(\tilde{x}) d\tilde{x}$ and

$$v(\tilde{x}) = \begin{cases} 1 & \text{if } \tilde{x} < 0.5 - a \\ \frac{1 - \varepsilon}{2a} (0.5 - a - \tilde{x}) + 1 & \text{if } \tilde{x} \in [0.5 - a, 0.5 + a] \\ \varepsilon & \text{if } \tilde{x} > 0.5 + a \end{cases}$$

with both a and ε positive and close to 0. The slope of the function $u(x)$ is equal to 1 for $x < 0.5 - a \approx 0.5$ and is equal to $\varepsilon \approx 0$ for $x > 0.5 + a$. Since the utility function associated to standard k ($=A, B$) stagnates once its market share has reached the threshold of $x_k = 1/2$, it would be optimal from the welfare point of view to split the market between the two standards when $\varepsilon < \beta < \frac{u(1)}{u'(0)} \approx \frac{1}{2}$ (or symmetrically when $\frac{1}{\varepsilon} > \beta > \frac{u'(0)}{u(1)}$), but despite this, standardization occurs.

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