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# Adoption Delay in a Standards War


by

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# Adoption Delay in a Standards War*

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**Abstract**

We analyze a dynamic model in which firms and consumers choose to adopt one of two technologies or delay their adoption. Adoption allows agents to trade with other adopters of the same technology. We show that there is an inefficient equlibrium in which firms differentiate across standards and consumers delay their adoption. With one standard, there is immediate adoption, which matches the experience of the 56K modem market.

JEL: L15, L10

## 1 Introduction

In early 1997, two groups of firms introduced 56K modems almost simultaneously. The modems were identical in the sense that they had the same performance characteristics but incompatible in the sense that if a consumer had a different standard then the consumer's Internet Service Provider (ISP), the modem was reduced to 33K. Sales were very disappointing for both technologies and the two sides, believing the standards war was to blame, turned to the International Telecommunication Union (ITU) to set a standard. The ITU issued the V.90 standard in early 1998 and modem sales increased dramatically immediately thereafter. Most previous theoretical models would predict that "tipping" would occur fairly rapidly in competition between two identical stan-

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dards. However, that was not the case here. Instead, the market required an intervention.[1]

This paper offers a new explanation for why we see adoption delay. We show that adoption failure can be the result of service provider incentives to differentiate across standards, even when consumers would prefer a unified standard. In the case of 56K, we claim that because ISP's differentiated across standards, consumers delayed their adoption decision, and *vice versa.* However, efficiency most likely called for early coordination on one standard or the other. In our model, as was true in the 56K market, adoption is slow under two standards but immediate under one standard.[2]

While our model is motivated by the 56K modem example, we believe that the model highlights issues that may be important in many markets with network effects. We consider a model in which there are two technologies available. In each period, consumers and firms choose to adopt a technology or wait until the next period. Consumers and firms that adopt the same technology may trade with each other, which is the sole value of technology adoption. The model exhibits indirect network effects in the sense that consumers benefit when other consumers choose their technology because more firms are attracted to the technology, which makes for a more competitive service. As this model is complicated, we solve for it numerically for representative parameter values. In this sense, the paper follows in the tradition of Pakes and McGuire (1994) and Ericson and Pakes (1995).

Our model exhibits two interesting equilibria. In the first, consumers adopt the technology that obtains a small early lead. Knowing this, firms also adopt the technology with a small early lead, which in turn justifies the consumers'

[1] A more detailed discussion of the industry can be found in Augereau, Greenstein and Rysman (2003), and Rickard (1997a, 1997b, 1998).

[2] Augereau, Greenstein and Rysman (2003) tests implications from this model in adoption data on ISP's. See Rolhfs (2001) and the cites therein for many examples of adoption failure in markets that exhibit network effects.

strategy. This "tipping" equilibrium is similar to previous research, such as Arthur (1989), and exhibits relatively quick standardization.

However, there is a second equilibrium that exhibits features that largely do not appear in the previous literature. In this equilibrium, a small group of technology-loving consumers adopt the technologies early but a large group of consumers delay their adoption until a critical mass of firms has picked one technology or the other. In this equilibrium, firms face a trade-off: if a firm adopts the technology with a small early lead, it raises the likelihood that it will ultimately be serving the large market. If a firm adopts the other technology, it faces less price competition in the short-run. When the short-run "incentive to differentiate" outweighs the long-run "incentive to coordinate," we observe firms splitting between the two standards. Then, it is a best response for consumers to delay their adoption decision. That is because observing a small early lead does not indicate that a technology will become the market standard. Relatedly, the longer consumers delay their adoption decision, the more attractive are the short-run benefits of differentiation to firms, so the strategies of delay and differentiation are mutually reinforcing. This equilibrium exhibits later standardization and is less efficient.

We show that whether this "delayed adoption" equilibrium exists depends on the relative strength of the network effect and the level of competition. If the network effect for firms is large (captured by the size of the group of consumers attracted to a popular standard), the incentive for firms to coordinate will be large and we cannot support an equilibrium with delayed adoption. However, if the market is very competitive (captured in this paper by a conjectural variations parameter), firms will not be attracted to a standard with other firms even if the size of the network effect is large. In that case, the incentive to differentiate dominates and an equilibrium with delayed adoption exists. One way for the social planner to eliminate the delay is to eliminate one of the standards, in which case the only equilibrium is for consumers to immediately adopt the remaining standard.

The early research on network effects is optimistic about the chances for relatively quick standardization.[3] In Farell and Saloner (1986a), a stream of consumers enter the market with rational expectations about the future and therefore all choose the same (possibly inefficient) standard. In Farell and Saloner (1986b), sequential decision-making leads to widespread adoption of a new technology, although they show that in a model with imperfect information, there can be adoption failure or a failure to standardize. Arthur (1989) is similar to Farell and Saloner (1986a) and shows that early adopters lead to tipping towards one technology or the other. Katz and Shapiro (1986a) exhibits a failure to standardize due to later generations of consumers valuing products differently then early generations - a form of intertemporal heterogeneity.

The above models study direct network effects in which no players has an "incentive to differentiate". More similar to our work is Chou and Shy (1990) and Church and Gandal (1992) which study indirect network effects similar to those in this paper, where consumers value other consumers adopting their hardware because it attracts more software providers. Church and Gandal (1992) in particular show that it is possible to have the market adopt two technologies when one would be preferable due to software providers incentive to differentiate across standards. Ellison and Fudenberg (2003) highlight similar issues in a more general setting. These models differ from ours in that they study static models in which all consumers adopt. We show in a dynamic setting that it is possible for consumer to choose not to adopt, a particularly inefficient result.

In summary, previous research considers models where the market chooses between two options, either old versus new technology or technology A versus technology B. Most previous research found "tipping" in markets with network effects. If they did not, they relied upon consumer heterogeneity (with the exception of Ellison and Fudenberg, 2003) and still found that all consumers

[3] See Shy (2001) for an introduction to research on network effects.

adopt. We show that combining the choice of A versus B with the option to not adopt creates a more complicated setting, one in which delay can arise even when goods are homogenous and adoption would be immediate if only one standard was available.

## 2 Model

This section presents a model of technology adoption under indirect network effects. There are two standards, $A$ and $B$. There are $n$ firms and a measure $\mu$ of atomistic risk-neutral consumers. In practice, we consider only $n = 3$. There are three types of consumers, types $A$, $B$ and $C$ with measures $\mu^A, \mu^B$ and $\mu^C$. Type $A$ consumers get higher utility from standard $A$ and type $B$ consumers get higher utility from standard $B$. Type $C$ consumers are indifferent between the standards and get less utility from the standards then $A$ and $B$ do from their preferred standard. We can think a $A$ and $B$ types as technology lovers.

The game is in discrete time with an infinite horizon. Each period has two stages. In the first stage, firms and consumers choose simultaneously whether or not to adopt one of the two standards. Firms and consumers cannot "un-adopt" after choosing to adopt, but choosing not to adopt allows them to adopt in a later period. Firms and consumers may not adopt both standards.[4] In the second stage, firms that have adopted set quantities to sell to consumers. Consumers may buy only from firms that have adopted the same standard. Otherwise, firms sell a homogenous product. Firms and consumers discount the future at a common discount rate $\beta$. We search for a Markov Perfect Bayesian Equilibrium.

Consumers pay a hardware cost $p_h$ for adoption, common to both standards. Consumer $i$ who has adopted standard $s$ observes per unit price $p_t^s$ in period

[4]Allowing for dual adoption makes the model more complicated although the results are similar.

$t$ and chooses quantity $q_{it}$. Each period, consumer $i$ who has adopted $s$ gets utility:

$$u^s_{it} = \alpha + q_{it} - \frac{q^2_{it}}{2\gamma^s_i} - p^s_t q_{it}.$$

Consumers with higher values of $\gamma^s_i$ derive higher utility from adoption. We assume $\gamma^A_A = \gamma^B_B > \gamma^A_C = \gamma^B_C = \gamma^B_A = \gamma^A_B$. Consumers that do not adopt or that adopt when no firms have adopted get a payoff of 0. Consumers solve the first-order condition:

$$1 - \frac{q_{it}}{\gamma^s_i} = p^s_t \Rightarrow q_{it} = \gamma_i(1 - p^s_t) \tag{1}$$

Total demand $q^s_t$ on standard $s$ is the integral of $q_{it}$ over the set of consumers who have adopted $s$:

$$q^s_t = \mu^s_t(1 - p^s_t) \Rightarrow p^s(q^s_t) = 1 - \frac{q^s_t}{\mu^s_t}.$$

We refer to $\mu^s_t$ as the demand level in period $t$ for standard $s$. In equilibrium, we will see that $\mu^s_t$ can take on one of three values. For the parameter values we analyze, type $A$ consumers adopt $A$ and $B$ consumers adopt $B$ in the first period, in which case $\mu^s_t = \mu^s\gamma^s_s$, $s = A, B$. It is also possible that $C$ types split between the two standards, so $\mu^s_t = \mu^s\gamma^s_s + \mu^C\gamma^s_C/2$. Finally, it may occur that $C$ types coordinate on a single standard $s$, in which case $\mu^s_t = \mu^s\gamma^s + \mu^C\gamma^s_C$.

Firms that adopt standard $s$ pay a one-time fixed fee of $F + \varepsilon^s_{jt}$, where $\varepsilon^s_{jt}$ is the fixed cost drawn by firm $j$ in period $t$ for standard $s$. While $F$ is known by all firms, $\varepsilon^s_{jt}$ is known only to firm $j$, although firms know that $\varepsilon_{jt}$ is drawn from the uniform distribution over $[0, 1]$.[5] Firms have a zero marginal cost of production. We take the actions of the owner of the technology to be fixed and exogenous. That is, $p_h$ and $F$ are exogenous parameters.

[5] Allowing cost shocks to be independent over time makes the analysis easier then if cost shocks were corellated over time, which allows us to focus on the economic issues we are interested in here. Levin and Peck (2003) consider an entry model in which firms draw a single cost shock that stays constant for the entire game.

We solve the production stage as a static Cournot game. While it may be possible to find equilibria where the production stage has dynamic features to it, looking for Markov Perfect equilibria rules out most of the possibilities. Let $n_t^s$ be the number of firms that have adopted $s$ in period $t$. In the second stage of period $t$, firm $j$ that has adopted standard $s$ solves:

$$\max_{q_{jt}} \pi_{jt}^s = p_t^s \left(q_t^s\right) x_{jt}^s \tag{2}$$

where $\pi_{jt}^s$ is the flow profit from production to firm $j$ that has adopted $s$, and $x_{jt}^s$ is the quantity produced by firm $j$ on $s$ in period $t$ so $\sum_{k=1}^{n_t^s} x_{kt}^s = q_t^s$. In equilibrium, flow profit from production to a firm that has adopted is:

$$\pi_{jt}^s = \pi(n_t^s, \mu_t^s) = \frac{\mu_t^s}{(n_t^s + 1)^2}$$

In addition, equilibrium price in period $t$ is $p_t^s = 1/(n_t^s+1)$ so $q_{it}^s = \gamma_i n_t^s/(n_t^s+1)$. Consumer utility can be computed accordingly. We denote equilibrium consumer surplus to a consumer of type $i$ in period $t$ on $s$ as $u_i(n_t^s)$. Note that because the model implies that price is independent of the demand level $\mu_t^s$, the consumer's flow utility does not depend on the adoption decision of other consumers.

The focus of this model is on the adoption decision. In this model, the state variables are the adoption decisions of firms and consumers in previous periods. We denote the history of decisions by firms and consumers in period $t$ with the vector $\mathsf{a}_t$.[6] As firms and consumers make adoption decisions simultaneously, they observe only $\mathsf{a}_{t-1}$ at the time of their decision. Note that time $t$ is not a state variable as it is not "pay-off relevant" in the sense of a Markov perfect equilibrium. The expected profit of adoption standard $s$ in period $t$ is:

$$\Pi^s(\mathsf{a}_{t-1}) - \varepsilon_{jt}^s = E\left[\sum_{\tau=t}^{\infty} \beta^{\tau-t}\pi(n_\tau^s, \mu_\tau^s)\,\middle|\,\mathsf{a}_{t-1}\right] - (F + \varepsilon_{jt}^s)$$

The expectation is taken over the future adoption decision of consumers and

[6] Define the vector $\mathsf{a}_0$ to be the vector denoting no adoption.

firms $n_t^s$ and $\mu_t^s$. A firm that waits receives:

$$\Pi^0(\mathsf{a}_{t-1}) = \beta E\left[\max\left(\Pi^0(\mathsf{a}_t), \Pi^A(\mathsf{a}_t) - \varepsilon_{jt+1}^A, \Pi^B(\mathsf{a}_t) - \varepsilon_{jt+1}^B\right)|\mathsf{a}_{t-1}\right]$$

Firm $j$ (that has not adopted) maximizes profit in period $t$ by choosing $d_{jt}^f \in \{0, A, B\}$ to maximize expected profit $\Pi_{jt}(d_{jt}^f, \mathsf{a}_{t-1}) = \{\Pi^0(\mathsf{a}_{t-1})$ if $d_{jt}^f = 0$, $\Pi^A(\mathsf{a}_{t-1}) - \varepsilon_{jt}^A$ if $d_{jt}^f = A$, $\Pi^B(\mathsf{a}_{t-1}) - \varepsilon_{jt}^B$ if $d_{jt}^f = B\}$.

A consumer $i$ that adopts $s$ in period $t$ receives:

$$V_i^s(\mathsf{a}_{t-1}) = E\left[\sum_{\tau=t}^{\infty} \beta^{\tau-t} u_i(n_\tau^s)\middle|\mathsf{a}_{t-1}\right]$$

A consumer that waits receives:

$$V_i^0(\mathsf{a}_{t-1}) = \beta E\left[\max(V_i^0(\mathsf{a}_t), V_i^A(\mathsf{a}_t), V_i^B(\mathsf{a}_t))|\mathsf{a}_{t-1}\right]$$

Consumer $i$ (that has not adopted) picks $d_{it}^c \in \{0, A, B\}$ to maximize $V_i(d_{it}^c, \mathsf{a}_{t-1}) = \{V_i^0(\mathsf{a}_{t-1})$ if $d_{it}^c = 0$, $V_i^A(\mathsf{a}_{t-1})$ if $d_{it}^c = A$, $V_i^B(\mathsf{a}_{t-1})$ if $d_{it}^c = B\}$.

We will also be interested the case where there is only one standard. The set-up is similar to the one above except that firms and consumers do not have the option to adopt standard $B$. In this case, firms draw only $\varepsilon_{jt}^A$. Firm $j$ (that has not adopted) maximizes profit in period $t$ by choosing $d_{jt}^f \in \{0, A\}$ to maximize expected profit $\Pi_{jt}(d_{jt}^f, \mathsf{a}_{t-1}) = \{\Pi^0(\mathsf{a}_{t-1})$ if $d_{jt}^f = 0$, $\Pi^A(\mathsf{a}_{t-1})$ if $d_{jt}^f = A\}$. Similarly, consumer $i$ (that has not adopted) picks $d_{it}^c \in \{0, A\}$ to maximize $V_i(d_{it}^c, \mathsf{a}_{t-1}) = \{V_i^0(\mathsf{a}_{t-1})$ if $d_{it}^c = 0$, $V_i^A(\mathsf{a}_{t-1})$ if $d_{it}^c = A\}$. Otherwise, notation is the same.

# 3 Computing Equilibrium

The adoption decision exhibits indirect network effects in the sense that a consumer may benefit from adoption by other consumers because it attracts more suppliers to the consumers' market, which lowers price. These models typically have multiple equilibria in subgame perfect (or sequentially rational) equilibria.

For instance, for any equilibrium adoption strategy, it may also be an equilibrium for all firms and consumers to wait three periods and then perform that adoption strategy. Gale (1995) considers these different types of equilibria in a related framework. Focussing on Markov perfect equilibria removes "waiting" scenarios, as the time period is not a payoff relevant state variable.

Static games of network effects typically also have equilibria where all agents play "do not adopt". However, a "no adopt" equilibrium is difficult to sustain in this dynamic setting. If the product is valuable to consumers and a firm did adopt, consumers would want to take advantage in later periods by adopting. So a firm would break a "no adopt" equilibrium, knowing it will induce the rest of the market to follow. Gale (1995) shows in a related set-up that there will always be adoption in finite time.[7]

Therefore, we have a stationary game in which strategies for firms $d^f(\mathsf{a}_{t-1})$ and strategies for consumers $d_i^c(\mathsf{a}_{t-1})$ are functions of previous adoption decisions. We search for symmetric strategies. We search for equilibrium by specifying consumer strategies $d_i^c(\mathsf{a}_{t-1})$ for $i = A, B, C$ , then computing the firms' best response $d^f(\mathsf{a}_{t-1})$ based on that consumer strategy, and then checking if there is a deviation $d_i^{c\prime}(\mathsf{a}_{t-1})$ that provides greater consumer surplus then $d_i^c(\mathsf{a}_{t-1})$.

For consumers, we consider five possible strategies. We believe these strategies span the set of possible equilibrium strategies. We call the first strategy *immediate adoption.* In this strategy, consumers adopt in the first period, before they observe the decisions of firms. Under *immediate adoption,* we assume consumers randomize between the two standards. Formally,

$$
\begin{aligned}
d_i^c(\mathsf{a}_{t-1}) &= A \text{ with } P = 0.5, B \text{ with } P = 0.5, \text{ if } n_{t-1}^A = n_{t-1}^B \\
&= s \text{ if } n_{t-1}^s > n_{t-1}^{-s}.
\end{aligned}
$$

[7] As stated above, we solve the production stage as a static game although it may be possible to sustain strategies with dynamic implications by conditioning on adoption decisions.

Also, we consider *coordinated adoption*, in which consumers immediately adopt and coordinate on a single standard. For instance, if *coordinated adoption* is focussed on $A$, then we have:

$$
\begin{aligned}
d_i^c(\mathsf{a}_{t-1}) &= A \text{ if } n_{t-1}^A \geq n_{t-1}^B + 1 \\
&= B \text{ if } n_{t-1}^B = 3
\end{aligned}
$$

Note that the second lines in the *immediate adoption* strategy and the *coordinated adoption* strategy are relevant only for out-of-equilibrium events. In our view, the *coordinated adoption* strategy is natural for the $A$ and $B$ types for whom it would be obvious which standard to focus on, but *immediate adoption* is more natural for $C$ types who are indifferent and have no coordinating device. We also consider the *small lead* strategy, where a consumer adopts the first standard to obtain a lead. Formally,

$$
\begin{aligned}
d_i^c(\mathsf{a}_{t-1}) &= s \text{ if } n_{t-1}^s > n_{t-1}^{-s} \\
&= 0 \text{ otherwise.}
\end{aligned}
$$

A fourth strategy is the *established standard* strategy, in which a consumer waits until at least two firms have adopted a standard. Formally,

$$
\begin{aligned}
d_i^c(\mathsf{a}_{t-1}) &= s \text{ if } n_{t-1}^s > 1 \\
&= 0 \text{ otherwise}
\end{aligned}
$$

In the *established standard* strategy, consumers that observe $n_t^A = n_t^B = 1$ wait until the third firm adopts to make their choice. We might imagine it is better to just adopt either standard at that point. This point leads us to our fifth strategy, the *small lead/adopt* strategy:

$$
\begin{aligned}
d_i^c(\mathsf{a}_{t-1}) &= 0 \text{ if } n_{t-1}^A = n_{t-1}^B = 0 \\
&= s \text{ if } n_{t-1}^s = 1, n_{t-1}^{-s} = 0 \\
&= A \text{ with } P = 0.5, B \text{ with } P = 0.5, \text{ if } n_{t-1}^A = n_{t-1}^B = 1 \\
&= s \text{ if } n_{t-1}^s > 1
\end{aligned}
$$

It would also be possible to create a coordinated version of *small lead/adopt,* which is not important for our purposes.

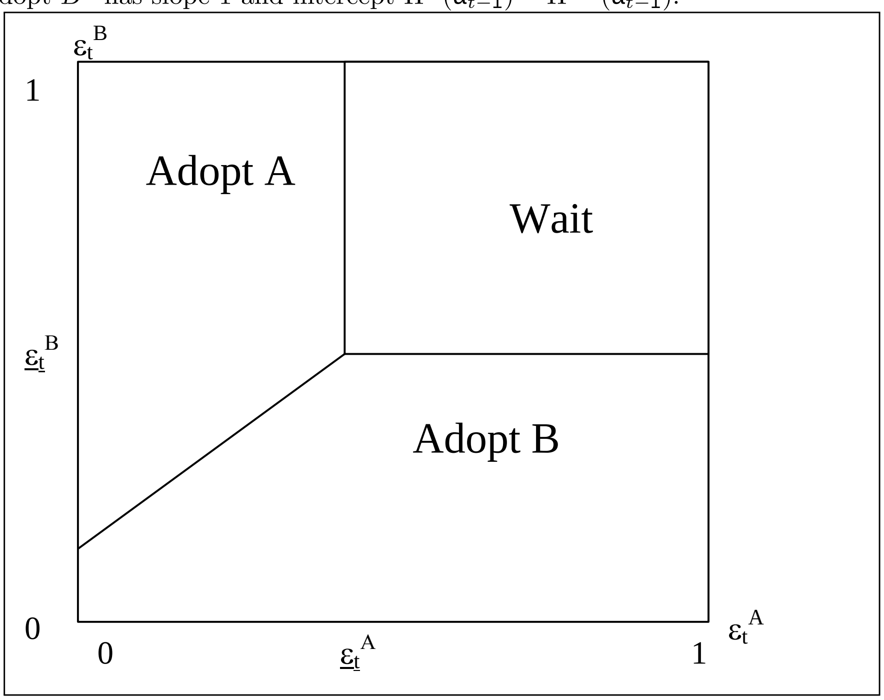
For any given set of parameters and a conjectured set of consumer strategies, we construct the firms' strategies $d^f(\mathsf{a}_{t-1})$. Because firms observe their own draws of $\varepsilon^s_{jt}$ but not those of their competitors, firms' strategies take the form of cutoffs. Firm $j$ in period $t$ prefers to adopt standard $s$ to waiting if $\varepsilon^s_{jt} < \underline{\varepsilon}^s(\mathsf{a}_{t-1})$ where $\underline{\varepsilon}^s(\mathsf{a}_{t-1})$ is defined by:

$$\underline{\varepsilon}^s(\mathsf{a}_{t-1}) = \Pi^s(\mathsf{a}_{t-1}) - \Pi^0(\mathsf{a}_{t-1}) \tag{3}$$

Firm $j$ in period $t$ plays a strategy $d^f(\mathsf{a}_{t-1})$ :

$$\begin{aligned} d^f(\mathsf{a}_{t-1}) \quad = \quad & s \text{ if } \varepsilon^s_{jt} < \underline{\varepsilon}^s(\mathsf{a}_{t-1}) \text{ and } \varepsilon^s_{jt} < \Pi^s(\mathsf{a}_{t-1}) - \Pi^{-s}(\mathsf{a}_{t-1}) + \varepsilon^{-s}_{jt} \quad s = A, B \\ & 0 \text{ otherwise} \end{aligned}$$

Figure 1 graphs this strategy in $\varepsilon^s$ space. The line separating "Adopt $A$" and "Adopt $B$" has slope 1 and intercept $\Pi^B(\mathsf{a}_{t-1}) - \Pi^{-A}(\mathsf{a}_{t-1})$.




Adoption probabilities

In practice, we compute the cutoffs $\underline{\varepsilon}^s(\mathsf{a}_{t-1})$ numerically. We set up the firm's problem as a Bellman's equation. For a given value function, we iterate best response cutoffs $\underline{\varepsilon}^s(\mathsf{a}_{t-1})$ until convergence. For a given set of cutoffs, we use value function iteration to solve for the value function. By iterating between solving for the cutoffs and value function, we solve for equilibrium cutoffs. The appendix discusses this procedure in more detail.

# 4 Equilibrium

The features of the equilibrium depend crucially on parameter values. Trying to characterize equilibria for the entire parameter set would be time consuming and not very informative. Instead, we choose a set of representative parameter values. In the next section, we perform comparative statics on important parameters. We believe that this approach conveys the insights of the model more effectively then an exhaustive discussion of all possible parameter values.[8] Consider the parameters $n = 3$, $\gamma_H = 5, \gamma_L = 1$, $\mu_H = 0.1$, $\mu_L = 1$, $F = 0.5$, $p_h = 0.5$ and $\beta = 0.8$. For these parameters, an individual $A$ or $B$ consumer demands 5 times as much quantity as a $C$ type, but total demand from $C$ types is still twice as much as from $A$ (or $B$) types. Note that for these parameters, $\pi(2, \mu^A\gamma_A^A + \mu^C\gamma_C^A) > \pi(1, \mu^A\gamma_A^A)$. That is, the network effect is large enough such that a firm would prefer to be a duopolist on the popular standard then be a monopolist on the unpopular standard.

For these parameter values, there are two equilibria that we discuss in this section, and a third that we discuss in the next section as it is more interesting in the context of discussing optimality. The first equilibrium that we consider is based on $C$ types playing *small lead*. Consider the following set of consumer strategies $d_i^c(\mathsf{a}_{t-1})$ :

[8] In this sense, this paper is similar to Ericson and Pakes (1995) and Pakes and McGuire (1994), and the literature that follows.

1. Type $A$ consumers play *coordinated adoption on A.*

2. Type $B$ consumers play *coordinated adoption on B.*

3. Type $C$ consumers play *small lead.*

Based on these consumer strategies, it is straightforward to compute cutoffs $\underline{\varepsilon^s}(\mathsf{a}_{t-1})$. Table 1 presents adoption probabilities for firms as functions of $n^A_{t-1}$ and $n^B_{t-1}$, assuming $C$ types have not yet adopted. For instance, if Firm 1 and Firm 2 adopt $A$ and $B$ in the first period, Firm 3 as a 27.1% chance of waiting in period 2, and otherwise is equally likely to pick either standard. The crucial line to observe is $n^A_{t-1} = 1$, $n^B_{t-1} = 0$ (note that $n^A_{t-1} = 0$ and $n^B_{t-1} = 1$ is symmetric). After observing one firm adopt, there is 43.9% chance that each remaining firm will adopt that standard and only a 26.2% chance that each firm will adopt the other. That is, firms are attracted to the standard that has a small lead. This feature both depends on and justifies the consumer strategy of adopting the standard with a small lead. Given the strategies for firms indicated in Table 1, a $C$ type receives expected utility 0.504 from playing *small lead*, 0.494 from playing *established standard,* 0.487 from *small lead/adopt* and 0.283 from *immediate adoption.*[9] Type $A$ and $B$ consumers are also best off with their strategies, expecting 3.42 from *coordinated adoption* and less then 3 from all other strategies.[10] Therefore, we have an equilibrium.

**Theorem 1** *$A/B$ types playing* coordinated adoption*, $C$ types playing* small lead*, and firms adopting according to $d^f(\mathsf{a}_{t-1})$, along with all agents believing $\varepsilon^s_{jt} \sim U[0,1]$ is a Markov Perfect Bayesian equilibrium*

[9] Note that when considering deviations by atomistic consumers, *immediate adoption* is equivalent to *coordinated adoption* for $C$ types.

[10] We have chosen $\gamma^A_A$ and $\gamma^B_B$ high enough that $A$ and $B$ types always adopt their preferred standard in the first period. The analysis would not be much different if we simply assumed that the game started with a group of consumers having already purchased each standard and only analyzed the $C$ types.

| Adoption Probabilities for Firms | | | |
|---|---|---|---|
| | Probability of Adoption | | |
| $n^A_{t-1}, n^B_{t-1}$ | None | A | B |
| 0,0 | 23.9% | 38.1 | 38.1 |
| 1,0 | 29.9 | 43.9 | 26.2 |
| 2,0 | 33.5 | 22.8 | 43.7 |
| 1,1 | 27.1 | 36.5 | 36.5 |

Table 1: Consumers play *small lead*.

This equilibrium exhibits "tipping." One standard obtains a small lead and the market flows towards that standard. This is the type of phenomena on which much of the previous literature on network effects has focussed.

However, our model exhibits a second equilibria that is different from what we have seen in previous work. Consider the game in which $C$ types play *established standard* instead of *small lead.* As before, $A$ and $B$ types play *coordinated adoption* on their preferred standard. Given these decisions by consumers, Table 2 presents adoption probabilities for firms. Again, focus on the case where $n^A_{t-1} = 1$ and $n^B_{t-1} = 0$. In this case, it is more likely that the remaining firms will adopt $B$, not $A$. Adopting $A$ in this situation would ensure a firm that it would serve the large market in the following period. But in the mean time, it must suffer through a period of duopoly competition over a small market. Instead, it prefers to go to the other standard, where it may be a monopolist.

Given these adoption probabilities by firms, we must check whether these consumer strategies are best responses. Type $A$ and $B$ consumers receive a lifetime expected utility of 3.61 from *immediate adoption.* All of the other strategies generate expected payoffs less then 3. Conversely, Type $C$ consumers who play *immediate adoption* receive expected utility of 0.12. Using *established standard* generates 0.484, *small lead* receives .482 and *small lead/adopt* generates 0.464.

| Adoption Probabilities for Firms | | | |
|---|---|---|---|
| | Probability of Adoption | | |
| $n_{t-1}^A, n_{t-1}^B$ | None | A | B |
| 0,0 | 16.4% | 41.8 | 41.8 |
| 1,0 | 22.4 | 31.4 | 46.2 |
| 2,0 | 26.2 | 25.9 | 47.9 |
| 1,1 | 21.7 | 39.1 | 39.1 |

Table 2: Consumers Play *Established Standard*

Therefore, we conclude that this set of strategies is an equilibrium.

**Theorem 2** *A/B types playing* coordinated adoption*, C types playing* established standard *and firms playing $d^f(\mathsf{a}_{t-1})$, along with all agents believing $\varepsilon_{jt}^s \sim U[0,1]$ is a Markov Perfect Bayesian equilibrium.*

A market observer would see a small group of technology lovers adopt one of the two standards immediately upon product introduction. A large group of consumers would wait until one of the standards obtained widespread market acceptance. The key feature to supporting this equilibrium is that firms prefer to differentiate rather then coordinate, as exhibited by the $n_{t-1}^A = 1, n_{t-1}^B = 0$ row. If a firm in this scenario were more likely to adopt $A$, then it would be difficult to support an equilibrium in which consumers wait for an *established standard.* Upon observing adoption by one firm, consumers would know that remaining firms are likely to choose that standard and then consumers themselves would adopt. The key to supporting *established standard* is that when consumers observe a standard achieve a small lead, it does not indicate that the standard will gain widespread acceptance. Similarly, consumer delay is crucial to support differentiation by firms. Because firms know consumers will delay their adoption, the short run benefits of differentiation are more valuable relative to the long-run benefits of coordination.

# 5 Optimality

Ignoring the per period adoption shocks, the optimal configuration for these parameter values would be to have all consumers and firms adopt in the first period, with two firms on the standard with the $C$ types and one firm on the other standard (see Thereom 7 in the appendix). With shocks, it can improve total welfare for a firm to wait for a good shock to adopt. However, equilibria in which consumers delay their adoption decisions are inefficient in expectation (see Theorem 8 in the appendix). A social planner that could not control the individual decisions of agents in the market would look for actions that move adoption forward in time.

We see two types of interventions that would be available to a realistic policy maker. One intervention is for the social planner to announce that $A$ or $B$ was the market standard. We can model this by assuming it moves the game from a *small lead* or *established standard* equilibrium to one in which all players play *coordinated adoption.* In fact, this consumer strategy can also be an equilibrium.

**Theorem 3** *$A/B$ types playing* coordinated adoption *on their preferred standard, $C$ types playing* coordinated adoption *on either standard, and firms playing $d^f(\mathtt{a}_{t-1})$, along with all agents believing $\varepsilon^s_{jt} \sim U[0,1]$ is a Markov Perfect Bayesian equilibrium.*

**Proof.** See appendix. ■

If all $C$ types adopted $A$ in the first period, firms would be likely to adopt $A$ and consumers would not want to deviate. Note that it cannot be an equilibrium for $C$ types to play *immediate adoption* under these parameter values. It must be that $C$ types coordinate on a single standard in the first period, so they are all likely to be served by two or even three firms. In the absence of government intervention, we find it implausible that $C$ types could manage to coordinate on a single standard.[11] However, it is certainly a believable result of a government

[11] We do not pursue formal equilibrium refinements that might restrict the number of equi-

intervention.

A second and very similar intervention would be for the social planner to eliminate one standard or the other, or to eliminate both and introduce a third standard. This puts the market in the game with one standard, discussed at the end of Section 2. In this game, none of the consumer strategies are an equilibrium except *immediate adoption* (which is equivalent to *coordinated adoption* when there is only one standard).

**Theorem 4** *In a game with one standard, all consumers adopting in the first period and firms playing* $d^f(\mathsf{a}_{t-1})$, *along with all agents believing* $\varepsilon_{jt}^s \sim U[0,1]$ *is the unique Markov Perfect Bayesian equilibrium.*

**Proof.** See appendix ■

There is no reason for consumers to delay when they know that firms will eventually adopt this standard.

# 6 Further Analysis

In the previous sections, we have analyzed the game for one set of parameter values. In this section, we explore other sets of parameter values in order to learn more about the model and verify that the intuition discussed above is accurate. This paper is primarily interested in the phenomena of adoption delay and we focus on the *established standard* equilibrium in this section.

The first issue we study is the role of network effects in determining the equilibria. Intuitively, it must be that for *established standard* to be an equilibrium,

libria in the model. However, note that *established standard* is less risky in a particular sense. If a $C$ type plays *coordinated adoption* or *small lead* and all other $C$ types and firms play according to *established standard,* the mistaken consumer may be stuck on the wrong standard forever. Conversely, the cost to a $C$ type that plays *established standard* when all other players play *coordinated adoption* or *small lead* is only that the mistaken consumer adopts the correct standard one period too late. That is, *established standard* risk dominates *small lead* and *coordinated adoption* in the sense of Harsanyi and Selten (1988).

the size of the network effect must not be too big. If the network effect is large, firms prefer coordination and it is no longer a best response for consumers to delay. It is natural to think of the parameters $\gamma_i^s$ and $\mu_i$ as governing the size of the network effect. For instance, as $\gamma_C^s$ or $\mu_C$ rises, the importance of the network becomes larger. That is, the impact of the decisions of the $C$ types becomes larger so they attract more firms to their standard. If $\gamma_C^s$ or $\mu_C$ was very large, firms would prefer coordinating with the $C$ types to serving the $A$ and $B$ types and the game would be as if there were homogenous consumers. Note that comparative statics in $\mu_i$ are easier to interpret then in $\gamma_i^s$ because $\mu_i$ does not affect any of the players' objective functions directly, only their strategies.

We begin our study of the model by reducing $\mu_A = \mu_B$ (which has the same effect as increasing $\mu_C$). Setting $\mu_A = \mu_B = 0.05$ (instead of 0.1) increases the attractiveness of selling to the $C$ types relative to the $A$ and $B$ types. Even if $C$ types play *established standard*, firms no longer prefer differentiation. Table 3 shows the best response probabilities for firms when consumers play *established standard.* When observing $n_{t-1}^A = 1$ and $n_{t-1}^B = 0$, the remaining firms still slightly prefer $A$ to $B$. In this case, consumers would prefer to adopt upon observing a single firm adopt because it is likely enough that they will be served by more firms, so *established standard* cannot support an equilibrium.[12] Therefore, as network effects become more important, inefficient delay (associated with waiting for an established standard) disappears. For the values $\mu_A = \mu_B = 0.05$, *small lead* can still support an equilibrium.

**Theorem 5** *For $\mu_A = \mu_B = 0.05$, $C$ types playing* established standard *cannot support an equilibrium although $C$ types playing* small lead *can.*

**Proof.** See appendix. ■

[12]The cut-off in $\mu_A/\mu_B$ at which *established standard* can no longer support an equilibrium is higher then $\mu_A = \mu_B = 0.05$ and occurs at a point were firms still slightly prefer differentiation to coordination.

| Adoption Probabilities for Firms | | | |
|---|---|---|---|
| | Probability of Adoption | | |
| $n^A_{t-1}, n^B_{t-1}$ | None | A | B |
| 0,0 | 35.4% | 32.3 | 32.3 |
| 1,0 | 36.7 | 32.7 | 30.6 |
| 2,0 | 39.8 | 35.3 | 24.9 |
| 1,1 | 31.1 | 34.4 | 34.4 |

Table 3: Consumers play *coordinated adoption*, $\mu_A = \mu_B = 0.05$.

The feature that can undo the impact of large network effects is the competitiveness of the market. Intuitively, if firms face a very competitive market after adopting, adopting the same standard as that of a competitor becomes less attractive and we will observe firms differentiating across standards instead of coordinating. We model this feature by introducing a conjectural variations parameter. Following the literature on conjectural variations, we specify the second-stage first-order condition for firms that face competitors to be:

$$p^s_t(Q^s_t) + \frac{\partial p^s_t(Q^s_t)}{\partial Q^s_t}\theta = 0$$

The parameter $\theta$ is a conjectural variations parameter. Setting $\theta = 1$ implies a Cournot game whereas setting $\theta = 0$ implies a Bertrand game. Lowering $\theta$ leads to a more competitive outcome, with lower prices and lower profits for firms.[13] For instance, consider $\theta = 0.5$, $\mu_A = \mu_B = 0.05$ and consumers playing *established standard*. In this case, equilibrium adoption probabilities are in Table 4. Note that now, firms that observe $n^A_{t-1} = 1$ and $n^B_{t-1} = 0$ are more likely to adopt $B$ so the incentive to differentiate outweighs the incentive

[13] Interpreting the parameter $\theta$ as a conjectural variation in the sense that the literature originally meant has well-known problems. (for instance, see Lindh, 1992) For our purposes, we think of it as just a convenient parameterization that indexes profitability and competitiveness of the market.

| Adoption Probabilities for Firms | | | |
|---|---|---|---|
| | Probability of Adoption | | |
| $n^A_{t-1}, n^B_{t-1}$ | None | A | B |
| 0,0 | 37.4% | 31.3 | 31.3 |
| 1,0 | 39.1 | 27.7 | 32.2 |
| 2,0 | 42.3 | 25.1 | 32.6 |
| 1,1 | 36.6 | 31.7 | 31.7 |

Table 4: Consumers play *coordinated adoption*, $\mu_A = \mu_B = 0.05, \theta = 0.5$.

to coordinate. And also, playing *established standard* is a best response for consumers so *established standard* is once again an equilibrium.

**Theorem 6** *For $\mu_A = \mu_B = 0.05$ and $\theta = 0.5$, A and B types playing* coordinated adoption *and C types playing* established standard, *and firms playing $d^f(\mathsf{a}_{t-1})$, along with all agents believing $\varepsilon^s_{jt} \sim U[0,1]$ is a Markov Perfect Bayesian equilibrium.*

**Proof.** See appendix. ■

We speculate that starting from a set of parameters for which *established standard* can support an equilibrium, it is always the case that the incentive for firms to coordinate can be increased via $\mu_i$ or $\gamma^s_i$ such that *established standard* can no longer be an equilibrium. However, we also conjecture that for any $\mu_i$ or $\gamma^s_i$, the competitiveness of the market can always be increased via $\theta$ such that *established standard* can once again be part of an equilibrium. That is, the possibility of adoption delay depends on the strength of the competing forces of network effects and competitiveness, driving the incentive to coordinate and the incentive to differentiate.

# 7 Conclusion

This paper presents a dynamic model of indirect network effects. With firms and consumers choosing between two different standards and having the option to delay adoption, we show for particular parameter values that an equilibrium exists in which consumers delay their adoption until one of the standards reaches a critical mass of firms. This "delayed adoption" equilibrium is less efficient then one in which firms and consumer adopt the standard that obtains a small early lead or one in which they manage to coordinate on a standard in the first period. When there is only one standard, immediate adoption is the only equilibrium strategy for consumers.

We believe that the original parameter values accurately reflect the market for 56K modems. That is, when there were two standards, the market was in an equilibrium based on *established standard* which entails significant delay. However, when the standard setting organization specified a new standard, there was effectively only a single standard which led to immediate and widespread adoption. We do not formally model the decisions of the sponsors of the technologies. However, one could imagine that they hoped to introduce their products into a market where consumers were playing *small lead.* Upon introducing the products, the sponsors realized that consumers and ISP's were adopting strategies of delay and differentiation. The sponsors then turned to the standard setting organization to eliminate the delay, even if it meant that the sponsors would have to compete using the same standard.

A testable implication from this model is that when observing products that fail to gain widespread acceptance due to a standards war, adopting firms should be differentiating across the standards, as opposed to coordinating. Augereau, Greenstein and Rysman (2003) provide empirical evidence that in the period before the ITU became actively involved, adopting ISP's differentiated across standards. That is, within local markets (which they treat as local calling areas), there were many more even splits between the two standards then would be predicted by independent random choice.

The issues highlighted in this model may be important in other industries. In particular, our model suggests that the competitiveness of the service market may be an important determinant in adoption success. For example, in the VCR industry, the firms in this model would be movie producers. One of many possible reasons that the VCR market was successful in coordinating on a single standard may be that movie producers choosing whether to produce for VHS or Beta (or both) knew that popular movies would be profitable on either standard, regardless of how many other prerecorded video tapes were available. This contrasts with the ISP market where facing even a small number of competitors could put ISP's in a very competitive situation, where it was difficult to recoup fixed costs.

# 8 Appendix

*Discussion of value function iteration:* Let $a_t$ be the 4×1 vector denoting the state in period $t$. The first 3 elements refer to the adoption decisions for firms 1 to 3 and may be equal to 1,2 or 3 denoting {have not adopted, have adopted $A$, have adopted $B$}. The remaining element denotes the decision of $C$ types and may be equal to 1,2,3 or 4 denoting {have not adopted, have split between $A$ and $B$, have adopted $A$, have adopted $B$}. There are 108 possible states. Let $V(a_{t-1})$ denote the value to firm 1 at the beginning of a period from being in any one of those states, defined by the fixed point:

$$V(a_{t-1}) = E[\pi(a_t) - F(a_{t,}a_{t-1}) + \beta V(a_t)|a_{t-1}]$$

where the expectation is taken both over the decisions of consumers and all the firms, including firm 1. The function $F(a_t, a_{t-1})$ represents the cost of adoption and is equal to $E[F + \varepsilon^s_{1t}|a_{t-1}]$ if firm 1 adopts (that is, $a^1_t > 1$ and $a^1_{t-1} = 1$) and 0 otherwise. The expectation is taken with respect to the probability density function generated by the cutoffs $\underline{\varepsilon}^s(\mathsf{a}_{t-1})$ and the decisions of consumers, which are a deterministic function of $a_{t-1}$. We can write $V(a_t)$ and $E[\pi(a_t) - F(a_{t,}a_{t-1})|a_{t-1}]$ as 108×1 vectors. We start with a guess for $V(a_t)$ and iterate to obtain convergence. We can also compute the value of a consumer at any given state:

$$V_i(a_{t-1}) = E[u_i(a_t) - p_h(a_{t,}a_{t-1}) + \beta V_i(a_t)|a_{t-1}] \; i = A, B, C$$

When we compute the value to a consumer from deviating from a proposed equilibrium strategy, we augment $a_t$ with an extra element which may take on 4 values and captures the decision made by the deviating consumer. In this case, the state space has 432 states.

*Proof of Theorem 3:* A type $A$ or $B$ consumer that adopts their preferred standard in the first period expects utility of 5.26 whereas *small lead/adopt* obtains 4.17, *established standard* obtains 4.04 and *small lead* obtains 4.06. Similarly for $C$ types, *coordinated adoption* obtains 0.65 whereas *small lead/adopt*, *established standard* and *small lead* obtain 0.567, 0.557 and 0.558 respectively.

*Proof of Theorem 4:* Suppose all consumers adopt in the first period. In this case, each firm adopts in the first period with probability 0.81. A firm adopts upon observing 1 other adopter with probability 0.59 and upon observing 2 other adopters with probability 0.5. Type $A/B$ consumers that adopt in the first period expect utility of 6.24, whereas waiting for one firm to adopt expects 5.11 and waiting for 2 adopters expects 5.03. Similarly for $C$ types, adopting in the first period obtains 0.85 whereas waiting for one adopter obtains 0.70 and waiting for two obtains 0.69.

Suppose $C$ types adopt after observing 1 firm adopt. In this case, each firm adopts in the first period with probability 0.55. However, even in this scenario, $C$ types obtain expected utility of 0.75 from adopting in the first period, 0.67 from waiting for 1 firm and 0.63 from waiting for 2 firms. Therefore, it is not an equilibrium for $C$ types to wait for 1 firm to adopt. Calculations are similar for $C$ types waiting for 2 firms. Therefore, $C$ types adopting in the first period is the unique equilibrium.

*Proof of Theorem 5:* Suppose $C$ types play *established standard.* Given the best response strategies of firms (summarized in Table 3), $C$ types obtain 0.472 from *established standard* and 0.484 from *small lead*, so this is not and equilibrium.

Suppose $C$ types play *small lead.* Given the best response strategies of firms, $C$ types obtain 0.515 from *small lead*, 0.497 from *small lead/adopt*, 0.494 from *established standard*, and 0.252 from *immediate adoption.* Types $A$ and $B$ get 3.25 from *immediate adoption* and 2.59, 2.29 and 2.18 from *small lead/adopt*, *small lead* and *established standard* respectively. Therefore, *small lead* is an equilibrium.

*Proof of Theorem 6:* Given the best response strategies of firms (summarized in Table 4), $C$ types obtain 0.778 from *established standard,* 0.775 from *small lead*, 0.734 from *small lead/adopt*, and 0.45 from *immediate adopt.* Types $A$ and $B$ get 4.29 from *immediate adoption* and 3.55, 3.23 and 3.09 from *small lead/adopt*, *small lead* and *established standard* respectively.

**Theorem 7** *The optimal configuration ignoring $\varepsilon_{jt}^{s}$ is to have all consumers and firms adopt in the first period, with tow firms on the standard with $C$ types.*

**Proof.** Assume 2 firms are on $A$. In this configuration, firms on $A$ make $\pi_{jt}^{A} = 0.167$ and the firm on $B$ makes $\pi_{jt}^{B} = 0.125$. Welfare to $A$ types an individual $A$ types is $u_A(2) = 1.11$, to $B$ type is $u_B(1) = 0.625$ and to a $C$ type is

$u_C(2) = 0.22$. Total welfare is $2\pi_{jt}^A + \pi_{jt}^B + \mu_A u_A(2) + \mu_B u_B(1) + \mu_C u_C(2) = 0.854$. An alternative configuration would be to have all firms and consumers on the same standard (suppose $A$), which obtains $\pi_{jt}^A = 0.1$, $u_A(3) = 1.41$ and $u_B(3) = u_C(3) = 0.28$, for a total of 0.75. Because firms and consumers always recieve positive payoffs from adoption as long as others adopt and receive zero for not adopting, adoption should take place as early as possible. ■

**Theorem 8** *Equilibria in which consumers delay their adoption decision are inefficient in expectation.*

**Proof.** In the equilibrium in which $C$ type consumers play *established standard*, expected profit for firms is 0.846, expected utility for $A$ and $B$ types is 3.41 and expected utility for $C$ types is 0.484, for a total expected welfare of 3.705. In the equilibrium in which $C$ type consumers play *small lead*, expected profit for firms is 0.849, expected utility for $A$ and $B$ types is 3.42 and expected utility for $C$ types is 0.504, for a total expected welfare of 3.734. In the equilibrium in which $C$ type consumers play *coordinated adoption*, expected profit for firms is 0.828, expected utility for $A$ and $B$ types is 5.26 and expected utility for $C$ types is 0.652, for a total expected welfare of 4.189. ■

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