

Competition, Inertia, and Network Effects*

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Abstract

We analyze a simple game of technology adoption with network effects and multiple new technologies. Potential adopters can adopt early, late, or not to adopt at all. We show that one of the reasons for the failure of new technologies can be the presence of multiple incompatible variants of that technology. An adopter's individual incentives to adopt are lower with multiple technologies than with one. Turning to aggregate expected welfare, however, we find that two active technologies may be welfare improving. *JEL: L1, O3. Keywords: Technology Adoption, Network Externalities, Installed Base.*

1 Introduction

Network effects, or demand interdependencies more generally, are known to lead to coordination failures in the context of new technologies: Potential future users look at past adoption decisions, current adopters form expectations about future generations, and so on. Unless prospective users can coordinate on a solution preferred by all (or most) of them, outcomes can be

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inefficient in the sense that either a new technology fails completely or that an inefficient technology is chosen.

In this context, we can think of coordination problems along two lines; old vs. new and new vs. new. The problem where a new technology fails to replace an established one due to coordination failures between imperfectly informed consumers has been discussed by Farrell and Saloner (1985), who have labelled this phenomenon 'excess inertia' — the socially suboptimal failure to adopt a new technology. The intuition is that potential adopters are deterred from switching because of the large installed base of the incumbent technology. The impact a large installed base can have on the success prospects of a new technology is illustrated in the following quote:

'Computers are a 'success' [...] since, unlike quad, there isn't another product to directly compete the way stereo was an alternative to quadraphonics.'¹

The issue of 'standard wars' between two versions of a new technology has been discussed by Arthur (1989), who illustrated the possibility of 'historical accidents' early in the technologies' history that may determine long-term market structure. A recent example of two new technologies competing for the new industry standard is DVD vs DivX. It has been argued that this co-existence had an impact on the diffusion speed of digital video on aggregate,² namely that

'[...]launching a competing format will confuse the consumers and confused consumers will not buy anything. The consumer acceptance of DVD will be delayed worldwide.'³

Both these statements however may only tell part of each story, given that there existed two versions of quadraphonic sound, and DVD and DivX were up against the sizeable installed base of analog VCRs.⁴ Therefore, the separate treatment of the two problems of old vs. new and new vs. new seems somewhat incomplete, at least in the context of the examples mentioned above. In both of these (and many others in the high-tech arena), multiple

¹<http://www.geocities.com/quadaudio/page14stillmorestuff.html>

²See, for example, Dranove and Gandal (2003).

³<http://www.robertsdvd.com/divx.html>

⁴Even in 2001, several years after the introduction of the DVD, approximately 90% of households still had a VCR (<http://www.centris.com>).

new technologies were trying (and some failed) to replace an established one. An interesting question to ask in this context therefore is: What is the impact of multiple new technologies on the likelihood of transition to a new standard, and what are the welfare implications of multiple new technologies entering?

We propose a simple game of technology adoption with network effects and multiple new technologies. In a two-period game with two heterogeneous adopters with imperfect information, we analyze the emergence of a *Bandwagon Equilibrium*, i.e. an equilibrium in which some types of adopters adopt early and others mimic the other's behaviour in the second period. This setup allows us to model a situation adopters may have different inherent (standalone) preferences, but total payoffs depend on each other's actions due to network effects, thus creating the possibility of coordination failures. Our model extends the existing literature by giving adopters in a new/new competition a fallback option (i.e. the option of not adopting), and adopters in an old/new setting now not only face the decision whether to adopt or not, but also which new technology to choose (if any).

There is a large number of articles that study the strategic adoption of network technologies. One strand of the literature revolves around the papers by Katz and Shapiro (1986), Choi (1994) and Choi and Thum (1998). These papers differ from ours in several important aspects: Especially, in their models homogeneous adopters arrive in an exogenously given sequence, which causes early adopters to impose a negative externality on latecomers (excess momentum or forward externality). In our model, the ordering and timing of moves is endogeneous and arises from the heterogeneity within the population. Our paper is therefore closest to Farrell and Saloner (1985), who study the adoption of a single new technology with heterogeneous adopters. In their paper, timing is endogeneous as well, and the source of inefficiency is the lack of coordination between adopters imperfectly informed about the other adopter's preferences.

This paper also contributes to the literature on irreversible investments and option value.⁵ Since adopters value compatibility with each other, there is an option value in waiting until the other adopter has made a decision. This option value, as we show in this paper, depends on the number of incompatible technologies on the market. Finally, another related strand of

⁵For an application of option value concepts to investments with network effects, see Mason and Weeds (2003).

literature is the work on entry into new markets.⁶ Geroski (2003) shows that many new markets go through the process of converging on a dominant design (Suarez and Utterback, 1995). On the way to a dominant design however, a significant number of alternative designs will fail. Since the cases in which a dominant design eventually emerged are almost always the successful ones, this paper adds to the literature by considering the possibility of complete failure of new technologies by addressing the effects of the entry of multiple designs on adoption behaviour. In other words, in our model expected aggregate demand is a function of the number of technologies in the market, which can have important implications for industry evolution, as we will show.

Our model explains several features of nascent network industries: We first show that in the presence of two competitively supplied new technologies, an adopter's equilibrium strategy may be not to adopt, even if she would have adopted had there been only one technology. This is expressed in an increase in the *critical value* (i.e. the minimum standalone valuation required) for 'unprompted' adoption, i.e. absent previous adoption by the other player. In other words, adopters that would have been willing to start a bandwagon with only one technology may not want to do this with two, leading to a *breakdown* of adoption. Second, even if an adopter finds early adoption profitable, she may prefer to delay adoption, thereby creating added potential for excess inertia – the socially inefficient failure to adopt a new technology. This is a result of certain types of adopters playing *mixed strategies* in the two-technology scenario. This again is a direct result of adopters' desire to be compatible with each other and may lead to a *slowdown* of adoption for particular types. Both effects lead to a lower adoption rate for a particular new technology – the critical value effect can, under some circumstances, generate zero adoption of both new technologies, while the mixed strategy effect may result in higher or lower overall adoption (and always lower adoption of any particular technology). On an aggregate level, we find that the effects of a second new technology on aggregate expected welfare depend on the distribution of adopters' preferences: Generally, if the likelihood of an adopter having a high valuation for any new technology is low, allowing multiple technologies in the market is welfare-enhancing. If the likelihood is high, however, multiple technologies are welfare-destroying.

The paper is structured as follows. The following section introduces the basic model and our equilibrium concept. Section 3 discusses equilibrium pa-

⁶See, e.g. Abernathy and Utterback (1978), or, more recently, Klepper (1996).

parameter spaces and behaviour for two technologies with independent values, and considers the special cases of a single new technology and two technologies with common values. In Section 4, we compare the one-technology and the two-technology cases in terms of critical values, equilibrium behaviour and expected aggregate welfare. We discuss limitations and possible extensions in Section 5 and conclude in Section 6.

2 The Model

■ **Setup of the game.** Consider two ex-ante symmetric agents i, j with private information about their preferences currently using an incumbent technology. Two new technologies x and y are supplied at marginal cost c . Switching can take place in periods $t = 1, 2$ or not at all. Adoption decisions are observed the end of each period. For simplicity, we ignore discounting and flow benefits.⁷ Adoption is irreversible and adopters will use at most one of the technologies.

□ **Realized Payoffs.** We normalize utility from the incumbent technology to 0. Net utility for new technology x consists of the standalone value a^x , and (common) network benefits b , and adoption cost c .⁸ If an adopter adopts new technology x , her realized utility at the end of the game will be

$$u_i^x(a_i^x, b, c, z_j^x) = a_i^x + bz_j^x - c \quad (1)$$

where $z_j^x = 1$ if player j has adopted x and $z_j^x = 0$ otherwise. The expression for y is formed accordingly. Network benefits thus only accrue if both adopters adopt the same technology.

□ **Valuations and Parameter Restrictions.** Standalone valuations for a technology x are $a^x \in \{h, l, 0\}$, where $h > l > 0$, and analogously for y .⁹ The realizations are private information, but it is common knowledge

⁷Considering discounting and/or flow benefits would generate the standard incentives to hasten adoption. Omitting these factors is in line with other papers that predominantly study coordination issues between adopters (see, e.g. Farrell and Saloner (1985), and Choi (1997)).

⁸Differences in adoption costs across agents are captured by differences in valuations for the new technology, and the assumption of common b is standard in the literature.

⁹We omit the subscript i, j where there is no ambiguity.

that they are drawn with probabilities p , q , and $1 - p - q$, respectively. An adopter's type is characterized by the valuation pair denoted $\mathbf{a} = (a^x a^y) \in \{(hh), (hl), (lh), (h0), (0h), (ll), (l0), (0l), (00)\}$. We write the probability of an adopter being of a specific type \mathbf{a} as $\phi_{\mathbf{a}}$. Denote by a_{\max} (a_{\min}) an adopter's weakly highest (lowest) valuation for the technologies. Figure 1 illustrates the valuation pairs and gives them intuitive labels. Note that a type's maximum valuation a_{\max} determines whether she is labelled an 'enthusiast', a 'follower', or an 'intransigent'. The difference between maximum and minimum valuation, $a_{\max} - a_{\min}$, on the other hand, indicates whether she is 'uniform' (if $a_{\max} = a_{\min}$), 'biased' (if $a_{\max} - a_{\min} = h - l$ or l), or 'stubborn' (if $a_{\max} - a_{\min} = h$).

$a^y = h$	stubborn enthusiast	biased enthusiast	uniform enthusiast
$a^y = l$	biased follower	uniform follower	biased enthusiast
$a^y = 0$	intransigent	biased follower	stubborn enthusiast
	$a^x = 0$	$a^x = l$	$a^x = h$

Figure 1: Valuation pairs and adopter characterizations.

Assume $b - c < 0$,¹⁰ and $l + b - c > 0$, so that an l -type would adopt a technology that carries the full network benefit (and, a fortiori, so would h -types). We can then focus on coordination issues among adopters and

¹⁰Farrell and Saloner (1985) demonstrate that their bandwagon result will only occur if there are some types, intransigents in their terminology, that would never adopt. The assumption that $b - c < 0$ and the possibility of zero valuation for a technology ensures this in our context.

technologies. Further suppose that $h < l + b$, which limits our analysis to the most interesting case where adopters may have a modest preference for one of the technologies but prefer to be compatible with the other player. Relaxing this assumption (so that $h > l + b$) would in fact make calculation simpler (because equilibrium strategies of hh - and hl -types would be identical), but less interesting.

□ **Actions and Strategies.** A player can adopt at most one new technology. An adopter's strategy $\sigma_{\mathbf{a}}$ consists of her adoption probabilities at each node in the game. Adopters face a decision node at $t = 1$ and in three subgames at $t = 2$.

Start of the game: At $t = 1$, adopt with probability $\alpha_{\mathbf{a}}$.

Subgame 1 (S1): At $t = 2$ if there has been no adoption in 1, adopt preferred technology with probability $\beta_{\mathbf{a}}$.

Subgame 2 (S2): At $t = 2$ if there has been adoption of one's preferred technology in 1, adopt preferred technology with probability $\gamma_{\mathbf{a}}$.

Subgame 3 (S3): At $t = 2$ if there has been adoption of one's less preferred technology in 1, adopt less preferred technology with probability $\delta_{\mathbf{a}}$.

An adopter's strategy for the entire game is denoted $\sigma_{\mathbf{a}} = \{\alpha_{\mathbf{a}}, \beta_{\mathbf{a}}, \gamma_{\mathbf{a}}, \delta_{\mathbf{a}}\}$.¹¹ Note that if $\alpha_{\mathbf{a}} + \beta_{\mathbf{a}} = 1$, the adopter is certain to adopt, and if $\gamma_{\mathbf{a}} = 1$, we label the adopter a 'bandwagon' adopter.¹²

□ **Equilibrium.** Every valuation pair \mathbf{a} maps into an equilibrium strategy $\sigma_{\mathbf{a}}^*$, i.e. the strategy maximizing expected payoffs. We solve for Perfect Bayesian Nash Equilibria in mixed strategies (PBNE). In other words, at every juncture of the game, player i 's action must maximize expected payoffs given current beliefs about j 's valuations. We are interested in settings

¹¹ Adopting one's preferred technology in $S \beta$ implies $a_{\max} > a_{\min} + b$. In this case, the equilibrium strategy would then be to adopt at $t = 1$ ($\alpha_{\mathbf{a}}^* = 1$), so that we ignore this theoretical possibility for notational convenience.

¹² A "Bandwagon Strategy", in Farrell and Saloner's (1985) terminology, involves delaying adoption at $t = 1$ and mimicking the other adopter's $t = 1$ action at $t = 2$. In our model, this may not necessarily be the case because an early adopter may adopt the less preferred technology and will consequently not be followed (if $\delta_{\mathbf{a}} = 0$). We stick to F/S' terminology however to describe the readiness to imitate adoption of one's own preferred technology.

where transition to the new technology is not guaranteed, but possible, and where some (types of) adopters need to be convinced to switch by observing prior adoption. We therefore concentrate on the parameter ranges in which there exist *Bandwagon Equilibria*:

Definition: A *Bandwagon Equilibrium (BE)* is a Perfect Bayesian Nash Equilibrium in which there is a positive probability of early adoption and there are types that would only adopt in 2 if there has been previous adoption.

This definition imposes restrictions on the values of h , l , b and c so that there exist valuation vectors \mathbf{a} such that some types of adopters will have optimal strategies $\alpha_{\mathbf{a}}^* = \beta_{\mathbf{a}}^* = 0$, $\gamma_{\mathbf{a}}^* = 1$, and some will play $\alpha_{\mathbf{a}}^* > 0$. The first condition basically requires that some adopters have a valuation high enough to adopt if they are guaranteed the network benefit and low enough to deter them from adopting on their own. The second condition says that some adopters value a new technology enough to consider switching early in order to get a bandwagon started. In the following section, we derive conditions for a *BE* to emerge.

3 Derivation of Equilibria

■ **Equilibrium analysis.** We are looking for the range and distribution of valuations (h, l, p, q) that will support a *BE*. For completeness, however, we first informally discuss equilibria that occur outside the relevant ranges.

□ **Non-bandwagon equilibria.** In a *BE*, some types will want to adopt early and some adopters want to follow. Therefore, if all h - and l -types adopt early (and 0-types never adopt), a *BE* would not ensue and the game would reduce to a standard coordination game between all types with $a_{\max} = h, l$. Emergence of this type of equilibrium depends on values of l and b in relation to c : High standalone valuations and network benefits for low-valuation adopters makes adopting with certainty a dominant strategy. We call this outcome a *coordination game equilibrium*. Conversely, if no adopter is willing to take the risk of adopting, a bandwagon will never get started and no adoption takes place. This *non-adoption equilibrium* will result from a low probability of being followed, i.e. low values of p and q , as well as relatively low standalone benefits h and network benefits b in relation to c , the cost of adopting.

□ **Bandwagon equilibria.** Consider the incentives of adopter i in a BE . Adopting at $t = 1$ may induce j to follow at $t = 2$ if she is playing a bandwagon strategy. Early adoption hence increases the probability of being followed. On the other hand, waiting until $t = 2$ lets i observe j 's move at $t = 1$ and react accordingly – there is an option value of delaying adoption. Intuitively, this suggests that adopters who care relatively little about being compatible with the other or are unlikely to change their behaviour in response to the other's behaviour – i.e. 'biased' or 'stubborn' types – will adopt earlier than adopters who are relatively indifferent between technologies and/or care about the network benefits more than the standalone value of the technology. The following proposition summarizes the properties of a BE in the case of two independent new technologies.¹³

Proposition 1a: *In the case of two independently drawn technologies, two BE exist, a high-adoption and a low-adoption BE . In the high-adoption BE , stubborn and biased enthusiasts adopt early with certainty, and uniform enthusiasts adopt early with probability $\alpha_{hh}^* = \frac{\frac{3}{2}p^2 - pq + q - p}{p^2}$. In the low-adoption BE , stubborn enthusiasts adopt early with certainty, biased enthusiasts adopt early with probability $\alpha_{hl}^* = \frac{p(1-p-q)(l+b-h) - \left(\frac{p^2}{2} + q\right)b}{pq(l+b-h) + pqb}$ and uniform enthusiasts delay with certainty. In both BE , followers play a bandwagon strategy.*

What distinguishes these equilibria and how do they form? In the high-adoption BE , a biased enthusiast will adopt early with probability 1. A uniform enthusiast – $\mathbf{a} = (hh)$ – anticipates this and mixes adoption times accordingly. On the other hand, if a biased enthusiast is expected to delay adoption with positive probability ($\alpha_{hl}^* < 1$), a uniform enthusiast will find it profitable to delay adoption altogether, i.e. $\alpha_{hh}^* = 0$. Therefore, biased and uniform enthusiasts will not mix strategies simultaneously since the option value of waiting differs between those types; Subgame 3 (following prior adoption of the less preferred technology) is worth more to a uniform than to a biased enthusiast, since $a_{\min}(hh) = h$ and $a_{\min}(hl) = l$. This implies that both types cannot be indifferent between adopting early and delaying for the same model parameters.

The mixing probabilities α_{hh}^* and α_{hl}^* are non-degenerate (i.e. $0 < \alpha^* < 1$) only for certain parameter ranges, as illustrated by Figure 2. If there is

¹³The proofs of all propositions are in the Appendix.

a high probability of the other adopter playing a bandwagon strategy, i.e. $a_{\max} = l$, even a uniform enthusiast will adopt early with certainty in order to start a bandwagon. As the ratio $\frac{p}{q}$ increases, the danger of a coordination failure due to simultaneous adoption of incompatible technologies increases and an indifferent adopter will delay with positive probability. If q decreases further, this tendency increases and the likelihood a of being followed by a bandwagon adopter decreases, thus resulting in mixing behaviour even by biased enthusiasts ($\mathbf{a} = (hl)$).

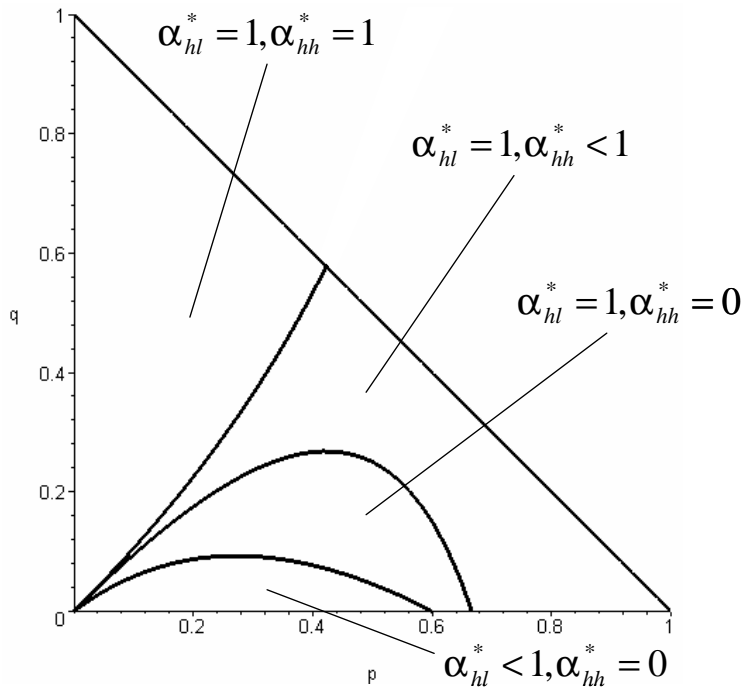


Figure 2: p, q ranges for non-degenerate mixed strategies. (Note: For α_{hl}^* , the following parameter values were used: $h = 2, l = \frac{7}{4}, b = 1$)

We now study two special cases of our basic model. First, we look at a single new technology instead of two. Second, we study two technologies that are perfect substitutes.

■ **Special case 1: Single new technology.** This case resembles Farrell and Saloner (1985). We use it as a benchmark to evaluate the changes when going from a single to two new technologies. Note that this is a special case

of our model where $a^y = 0 \quad \forall \mathbf{a}$. The incentives for adopters to adopt early or wait are similar with the important exception that adopting simultaneously is not risky in the sense that two adopters may not adopt the same technology and lose out on the network benefit.

Proposition 1b: *A BE in the one-technology case consists of an enthusiast adopting early with certainty and followers playing a bandwagon strategy.*

The intuition behind this *BE* is straightforward: If an adopter has a sufficiently high expectation of being followed in relation to her standalone valuation, she will adopt at $t = 1$. There is no incentive for an enthusiast to mix adoption times – if early adoption is profitable, it never pays to delay.

■ **Special case 2: Perfect Substitutes.** It is often argued that new technologies are more or less identical, i.e. that they target the same customers. This can be modelled as $a_{\max} = a_{\min} \quad \forall \mathbf{a}$. Suppose further that there is no focal point, i.e. adopters do not automatically coordinate on x or y if they are indifferent between the two.¹⁴ The *BE* then becomes the following.

Proposition 1c: *The unique BE in the case of two perfect substitutes involves enthusiasts adopting early with probability $\alpha_h^* = \frac{1}{2} + \frac{q}{p}$ and followers playing a bandwagon strategy.*

This result highlights one effect at play when there are multiple new technologies: Introducing an identical but incompatible technology creates a danger of failing to coordinate on a single new technology. In the one-technology scenario there was only the risk of the other adopter being an intransigent (with valuation $\mathbf{a}_{\max} = 0$), there is now the added possibility of a adopter moving simultaneously, but choosing an incompatible technology. This implies that for some parameter values, an enthusiast will delay adoption with positive probability ($\alpha_h^* < 1$). Existence of a *BE* in the case of perfect substitutes then implies that expected adoption (weakly) decreases.

¹⁴This assumption has been shown to alleviate at least some coordination failures in Katz and Shapiro (1986). In our model, assuming that within-generation coordination is possible would render the perfect substitutes case equivalent to the single-technology case.

4 Analysis

■ **From one to two technologies: Individual behaviour.** The difference in individual incentives to adopt between a single and multiple new technologies is apparent firstly in the average maximum valuation, in critical values, \hat{h} (\tilde{h}) and \hat{l} (\tilde{l}), respectively, and in the probability of adopting early, α_a^* .

□ **Average valuation.**

Proposition 2: *For two technologies with uncorrelated valuations, the average expected valuation increases.*

This Proposition, illustrated in Figure 2, shows that consumers, were there no issues of network effects and compatibility, would benefit unanimously from greater variety.¹⁵ While this is intuitive, it is nevertheless an important effect that originates from the provision of a second new technology. Given that in a *BE*, $a_{\max} = h$ implies that early adoption is profitable, this may also translate to a higher likelihood of early adoption – depending of course on α_{h0}^* , α_{hl}^* and α_{hh}^* , the probabilities for early adoption for enthusiasts.

The left picture depicts the one-technology case with just technology x on the market. The right shows that if an independent second technology is on the market, the maximum valuation is higher (by Δa_{\max}) in the shaded areas and unchanged elsewhere.

□ **Critical Values.**

Proposition 3: *In the two-technology case, the critical values for a *BE* to obtain are higher for enthusiasts and followers.*

Proposition 3 states that an enthusiast will require h to be higher in the two-technology case for her to adopt early. Similarly, an adopter with $a_{\max} = l$ will not adopt early (and consequently play a bandwagon strategy) for higher values of l . The intuition behind this result is simple: Recall that all critical values can be expressed in the form $c - f(p, q)b$, where $f(p, q)$ is the probability that both adopters switch to the same network. Expected

¹⁵This is considered one side of the tradeoff concerning product variety (Lancaster, 1990). In our model, the classical counterpart of the tradeoff is not modelled, i.e. there is no 'cost' of variety in the sense that new variants carry no development or other introduction costs.

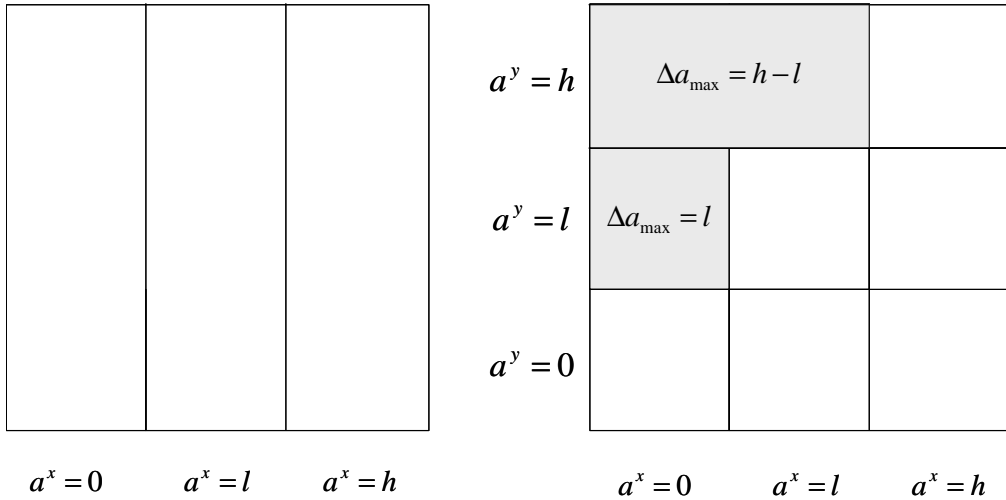


Figure 3: Change in maximum standalone valuations with two new technologies.

network benefits with two-technologies are lower because x -enthusiasts in the single technology case may now prefer technology y – in other words, the market may split between x - and y -enthusiasts, some of whom would have been happy with x as well.

The increase in critical values can have dramatic effects on adoption outcomes: For $h \gtrsim \tilde{h}$, adding a second technology may kill off the market entirely, because the expected network benefits from starting a bandwagon are not high enough to warrant starting it. To see this, consider a simple example: Suppose $a_{\max}^x = h = \tilde{h} + \varepsilon$, which would be sufficiently high to trigger adoption of x in the one-technology case. In the presence of two technologies however, h is below the critical value, i.e. $\tilde{h} < h < \hat{h}$, so that no adoption takes place at all.¹⁶

□ **Mixed strategies.**

Proposition 4: *In a BE, the probability of adopting early is weakly lower*

¹⁶We can of course construct an intermediate case in our model with four types in order to obtain a more moderate decrease in expected adoption: Very high ($a_{\max} \gg \tilde{h}$), high ($a_{\max} = \tilde{h} + \varepsilon$), l and 0 . High types would drop out and overall expected adoption decreases.

for enthusiasts.

This Proposition states that even within the range of a *BE*, an adopter's incentive to adopt early is weakly lower. The reason is that for some parameter ranges, $\alpha_{\mathbf{a}}^*$ is a non-degenerate mixed strategy (i.e. $0 < \alpha_{\mathbf{a}}^* < 1$) in the two-technology case, whereas it is always a pure strategy in the one-technology case. This is because there is no tradeoff in the one-technology case: The danger of attempting to start a bandwagon that does not succeed is already incorporated in the expected network benefits term determining the critical value. Therefore, if a_{\max} exceeds the critical value for early adoption, adopting early is a dominant strategy. On the other hand, with two technologies there may be an added benefit of waiting, triggered by trying to avoid a simultaneous switch to incompatible technologies. This tradeoff only affects an adopter's behaviour if the benefits from compatibility are important relative to the standalone value. In other words, for the second technology to have an impact on adoption behaviour in a *BE*, two conditions have to be met: First, the probability of the other adopter adopting early must be sufficiently high (i.e. $\sigma_{\mathbf{a}}^* = \{\alpha_{\mathbf{a}}^*, \cdot, \cdot, \cdot\} | \alpha_{\mathbf{a}}^* > 0$). Second, the difference between a_{\max} and a_{\min} must be sufficiently small. To see this, consider two types of enthusiasts: $\mathbf{a} = (h0)$ and $\mathbf{a} = (hh)$. A stubborn enthusiast would not change her behaviour anyway as a reaction to the other adopter's decision, while a uniform enthusiast is more concerned about being compatible with the other adopter because the specific variant of the new technology is not important as long as one of them gets adopted. Therefore, the incentive to delay increases as a_{\min} increases, which means that the probability of early adoption is weakly decreasing with a_{\min} for $a_{\max} = h$, i.e. $\alpha_h^* = \alpha_{h0}^* \geq \alpha_{hl}^* \geq \alpha_{hh}^*$.

■ **From one to two technologies: Welfare comparison.** We now turn to aggregate outcomes. We focus on *ex-ante* aggregate expected welfare; that is, we consider the likelihood that two adopters of types \mathbf{a}_i and \mathbf{a}_j meet and the welfare that ensues if they play out the game. For example, consider two adopters, one being a stubborn enthusiast and the other being a uniform follower. The likelihood of this occurring is $\phi_{h0}\phi_{ll} = p(1-p-q) \cdot q^2$, and the aggregate utility is $(h+b-c) + (l+b-c)$.¹⁷ Expected aggregate welfare is therefore the weighted (by their likelihood) aggregate payoffs of all possible

¹⁷A stubborn enthusiast adopts at $t = 1$ with certainty and a uniform follower adopts the previously adopted technology at $t = 2$. This results in both adopters gaining network benefits b on top of their net standalone benefits $h - c$ resp. $l - c$.

outcomes of the game. We thus can generically write welfare as follows:¹⁸

$$W = \sum \phi_{\mathbf{a}_i} \phi_{\mathbf{a}_j} (u_{\mathbf{a}_i} + u_{\mathbf{a}_j})$$

For the case with two perfect substitutes, it is simple to show the following:

Lemma 1: *Introducing an incompatible, perfectly substitutable technology is welfare-decreasing.*

Here we find the general gist of our results on individual adoption incentives confirmed: A second, identical technology is socially harmful. As we have shown in our analysis on individual incentives, adoption may either break down completely, and even if it does not, expected welfare is lower. As there are no benefits from variety (since valuations for both products are identical), the situations in which adopters move simultaneously, but choose different technologies would have resulted in a welfare-superior outcome in the one-technology case.

□ **Aggregate welfare, independent technologies.** As indicated in Proposition 2, the negative effect of a coordination failure with two incompatible technologies may be offset by the higher likelihood of an adopter being an enthusiast for one of the technologies. Since we are studying bandwagon equilibria, being an enthusiast implies that there is at least some probability of adopting early (see Proposition 1a). Proposition 5, illustrated in Figure 4, now specifies the conditions under which the 'variety effect' outlined in Proposition 2 can dominate the 'coordination effect' that underlies Lemma 1.

Proposition 5: *If p is sufficiently high, two independent new technologies will lead to lower expected aggregate welfare than a single one. Conversely, if p is low and q sufficiently high, two technologies may be welfare superior.*

An intuitive reading of this result goes as follows; giving potential adopters a second choice in a situation where it is likely that a bandwagon for a single new technology would get started anyway will only confuse consumers. This is likely to be the case when p , the likelihood of an adopter having a high valuation for a specific new technology, is sufficiently high. The effect

¹⁸The explicit expressions for expected aggregate welfare for the the cases we consider (two uncorrelated technologies, single technology, and two perfect substitutes) can be found in the Appendix.

of introducing a second new technology is then to increase the chances that adopters will fail to coordinate on a single new technology à la Lemma 1. On the other hand, if the likelihood of adopters being enthusiasts for any new technology is small (i.e. p small) and at the same time the proportion of potential followers is sufficiently large (i.e. q large), offering more variety in the market in order to get a bandwagon started is beneficial. That is, in cases where excess inertia is most prevalent (due to the high likelihood of l -types playing a bandwagon strategy), adding another new technology will improve expected welfare.

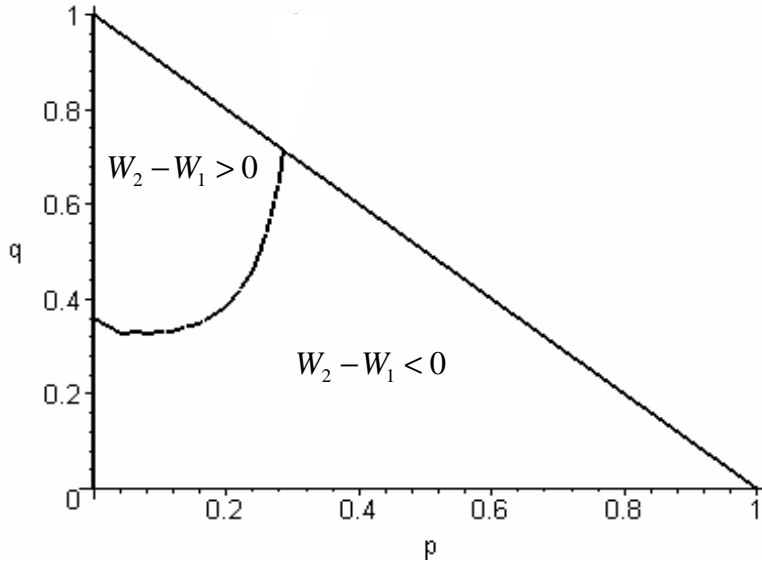


Figure 4: Parameter ranges for which adding an uncorrelated technology increases (decreases) aggregate welfare. (Note: Parameter values used were $h = 2$, $l = \frac{7}{4}$, $b = 1$, $c = \frac{27}{10}$)

5 Discussion and Limitations

■ **Discussion.** Our model, stylized as it is, isolates a number of mechanisms that are likely to persist even in more complex settings. In particular, the two general effects we identify are the *variety* and the *coordination effect*. Revisiting the two examples from the introduction, we can discuss the two

effects in these particular cases. In both cases however, other factors were at play, some of which will be discussed in the 'Limitations' section. In the case of DVD versus DivX, the general intuition was that '[...] home A/V enthusiasts interested in replaying movies tend to buy open DVD players, while heavy renters gravitate toward Divx.'¹⁹ While this seems to suggest that there was a variety effect did exist (since both technologies appealed to different types of consumers), the important question to ask is if adopters that opted for one of the systems would not have adopted the other system as well. In other words, did 'followers' become 'biased enthusiasts' and 'intransigents' become 'stubborn enthusiasts' because a second technology was available? Dranove and Gandal (2003) study the DVD versus DivX episode and find that overall sales of digital video decreased rather than increased with the preannouncement and eventual sales of DivX. This suggests that the coordination effect was not offset by the increased variety effect. This result seems to be confirmed by Augereau, Greenstein and Rysman (2004) in the market for 56k modems, where adoption figures by Internet Service Providers (ISPs) were significantly lower while a standard had not been established. In their case, the lack of a variety effect is even more stark since the two standards were functionally identical but incompatible.

■ **Limitations and extensions.** Although we believe that the model captures a number of interesting features of emerging markets with network effects, there are some limitations that need to be addressed.

□ **A-priori symmetry.** Both technologies, if active, are assumed to be symmetric ex-ante. That is, the high, low, and zero valuations are equivalent for both technologies, as are the network benefits and the exogenous switching costs. Changing any of these assumptions would obviously tip the game in the better technology's favour. If one technology was unanimously preferred by all adopters so that $l_x > h_y$, and the other parameters of the model would remain the same, the coordination problem would not arise. If, however, technologies would only be ordered within the high and low valuations, i.e. $h_x > h_y$ and $l_x > l_y$, the coordination problem would still remain, albeit weaker. An interesting case to look at in future research is where the distributions of valuations for different technologies differ. For example, if a technology has many prospective followers, but very few enthusiasts in

¹⁹<http://www.techweb.com/wire/story/TWB19990326S0014>

its favour, while another one has comparatively more trendsetters but less followers, we may obtain a scenario where a switch to the 'mass-market' technology (higher q , lower p) would be efficient, but the 'trendy' technology is more likely to succeed. This will of course also have implications for firm behaviour – for instance, Urban and von Hippel (1988) have found that for the computer-aided design of printed-circuit boards (PC-CAD), variants of the product that have been designed according to lead users' preferences have been comparatively more successful than ones that were not.

□ **Competitively supplied technologies.** We treat c as an exogenous parameter in our model. If a technology is sponsored, however, price may be a decision variable by the firm(s). In fact, Katz and Shapiro (1986) have shown that a sponsored technology has an advantage over an unsponsored one even if it is inferior. On the other hand, they show that in a competition between two sponsored technologies, the technology which will be superior later on has an advantage. Their results do not necessarily apply to our case however since they only model one old (superior today) and one new (superior tomorrow) technology. In our model, the effect of increased competition with a second technology will bias the results in favour of the two-technology case. Even if the variety effect is moderate, having two sponsors heavily subsidizing adoptions in the first period in order to get a bandwagon started may make the transition to a new technology more likely in the two-technology case than in the one-technology (monopoly) case. Our model however mainly aims to capture the demand side of the problem.

□ **'Large' adopters.** In our model, in line with previous models on strategic technology adoption, adopters are 'large' in the sense that the adoption decisions are directly interdependent. This is realistic in a setting where players are firms, or where network effects are localized to an extent that consumers observe directly each other's decisions. Considering a model in which individual adopters have measure zero would generate a process more comparable to standard diffusion models and an adopter's decision to adopt would be based on an aggregate adoption figures.²⁰ Work in this spirit has been done by Koski (1999) and Berndt et al. (2003), who estimate the impact of competition between multiple variants of a new product (PCs and

²⁰Note that adopters may still form expectations about the aggregate number of adoptions, but they expect the individual effect of their decision to be zero.

Antiulcer drugs, respectively) on diffusion speed.

□ **(In-)Compatibility.** Our model assumes that new and old technologies are not compatible, which makes adopters reluctant to switch in the first place. In fact, choosing compatibility between the new technologies would unambiguously improve matters: As long as the loss in variety (through fixing some of the product characteristics that contribute to variety in the first place) is not too big, it may be preferable in some circumstances to sacrifice some variety by ensuring some degree of compatibility between competing technologies. David Taylor, Commercial Director of Orange, the UK mobile phone operator, spells out this notion by suggesting that:

[...] network operators, handset manufacturers and the whole industry must work together to grow this market. That means we at Orange will be calling for network interoperability.²¹

Another facet of compatibility choice is the decision to make the new technology compatible with the incumbent one. Choosing backward compatibility would increase the valuation for each adopter by λb , where $0 \leq \lambda \leq 1$ is the degree of backward compatibility. If this increase is uniform across adopters and technologies however, this is identical to lowering the switching cost to $c - \lambda b$. If only one new technology is backward compatible (for example because it is owned by the dominant firm in the old technology), this will modify the results as if there was vertical differentiation: If an adopter has equal standalone valuations for both technologies, the network benefit will cause him to prefer the backward compatible technology. Thus, if backward compatibility is important (i.e. λb large), this may even lead to a situation where one technology is unanimously preferred, so that $l_x + \lambda b > h_y$.

6 Conclusion and Implications

The analysis of strategic technology adoption has so far focused on competition between two technologies, either a new and an old or two new ones. In this paper, we focus on the situation where potential adopters have the choice between one of two new technologies or not adopting at all. We contrast our finding with the previous results by Farrell and Saloner (1985) and find that,

²¹ *The Independent*, Tuesday 13th August 2002, page 16.

compared to their case with a single new technology, multiple technologies will raise the threshold for any early adoption to occur. In other words, an adopter must have a higher valuation for a new technology to find it worthwhile adopting in the presence of multiple new technologies. Further, we find that even if this threshold is met, adopters with valuations that would warrant early adoption may find it profitable to delay. Both these effects arise because of the danger of coordination failures between adopters – the first effect comes from the lower expected network benefit from adopting a technology; this makes adoption less desirable, which results in a higher critical value for adoption. The second effect emerges because high-valuation adopters are basically playing a coordination game; on the one hand, they would like to start a bandwagon because they would favour a switch, but on the other hand they would prefer someone else starting it so that they can ensure compatibility by adopting the same. If the probability of early adoption is sufficiently high, an adopter may therefore delay her move, and again a bandwagon may not get started. The final question we study is the effect of multiple technologies on aggregate welfare. Calculating expected aggregate welfare, we find that even though the probability of 'orphaning' – i.e. being the sole adopter of a new technology increases compared to a single new technology, there are parameter ranges for which expected welfare is higher with two technologies. We interpret this as the variety effect – multiple imperfect substitutes on the market increase the probability that there will be an adopter sufficiently motivated to risk starting a bandwagon.

Our simple model could be extended in several directions. New technologies, as mentioned earlier, are often introduced prematurely, an element that is not reflected in our model, since the qualities of the new technologies are given exogenously. Quality competition or R&D rivalry would be a promising line of research that might expand our knowledge about the dynamics of product introduction into markets with network externalities. Also, it would be interesting to allow for product preannouncements in our model, since this would present a more realistic intermediate case between multiple simultaneous technologies and a single new technology.

A Proof of Propositions 1 - 5 and Lemma 1

A.1 Preliminaries

■ Equilibrium Conditions (p. 5).

We start with some notation. Denote as u_S , $S \in \{S1, S2, S3\}$ the expected net utilities in the three subgames at $t = 2$, and U_t , $t = 1, 2$ the expected utilities from adopting early or delaying. Recall that $\phi_{\mathbf{a}}$ is the probability that an adopter is of type \mathbf{a} . Further, we define ρ_1 as the probability of early adoption of a specific technology (so that the probability of any technology being adopted is $2\rho_1$), ρ_2 the probability of late adoption in $S1$, and ρ_F the probability of an early adoption being followed. With this notation, we can now outline the conditions for a BE to form.

Subgames $S2$ and $S3$ are easy to solve. An adopter in $S2$ ($S3$) will simply consider whether u_{S2} (u_{S3}) > 0 , i.e. $a_{\max}(a_{\min}) + b - c \gtrless 0$ and adopt accordingly.

$S1$ requires updating expectations about the other adopter; player i knows that $S1$ could have been reached only if the other adopter would not adopt early with certainty, i.e. $\alpha_{\mathbf{a}_j}^* < 1$. Therefore, $\beta_{\mathbf{a}}^* = 1$ ($\beta_{\mathbf{a}}^* = 0$) if $a_{\max} + \rho_2 b > (\leq) c$.

We can now determine whether or not to adopt at $t = 1$. In short, if $U_1 > (<) U_2$, $\alpha_{\mathbf{a}}^* = 1$ (0), and if $U_1 = U_2$, $0 \leq \alpha_{\mathbf{a}}^* \leq 1$ given that $U_1 \geq 0$. Adopting at $t = 1$ gives $a_{\max} - c + (\rho_1 + \rho_F)b$. The final term is the network benefit times the probability of simultaneous adoption of the same technology at $t = 1$ plus the probability of being followed at $t = 2$. Delaying adoption gives an adopter flexibility to wait and observe which subgame is played at $t = 2$, and play her optimal action for each subgame. The expected value from delaying therefore are the utilities in each subgame weighted by each subgame's likelihood of occurring. We therefore get the following condition for early adoption:

$$a_{\max} + (\rho_1 + \rho_F)b - c > (1 - 2\rho_1)u_{S1} + \rho_1 u_{S2} + \rho_1 u_{S3}$$

To make the adoption probabilities ρ . more precise, we write:

$$\begin{aligned}
\rho_1 &= \sum \phi_{\mathbf{a}} \cdot \alpha_{\mathbf{a}}^* \\
\rho_2 &= \frac{1}{2} \sum \phi_{\mathbf{a}} \cdot \max [0, (\beta_{\mathbf{a}}^* - \alpha_{\mathbf{a}}^*)] \\
\rho_F &= \frac{1}{2} \sum \phi_{\mathbf{a}} \cdot (\max [0, (\gamma_{\mathbf{a}}^* - \alpha_{\mathbf{a}}^*)] + \max [0, (\delta_{\mathbf{a}}^* - \alpha_{\mathbf{a}}^*)])
\end{aligned}$$

Lemma A1: For ex-ante symmetrical technologies, $\rho_F \geq \rho_2$.

Proof: $\beta_{\mathbf{a}} \geq 0$ implies that $a_{\max} + \rho_2 b \geq c$. Since $\rho_2 \leq 1$, $a_{\max} + b \geq a_{\max} + \rho_2 b$, so that $\gamma_{\mathbf{a}} \geq \beta_{\mathbf{a}}$. Therefore, the first term in large brackets in ρ_F , i.e. the number of "happy followers" – followers that end up adopting their preferred technology – is already at least as large as ρ_2 , so that $\rho_F \geq \rho_2$. ■

Lemma A1 states that it is more likely to find followers for one's preferred technology than "unprompted" adopters in 2. For ex-ante identical technologies, the total mass of adopters wanting to adopt in S_1 will split evenly among the technologies. The adopters ready to adopt their preferred technology regardless of previous adoption would adopt even more readily if guaranteed the network effect ($\rho_F \geq \rho_2$).

Further, the following relations between expected utilities of different types hold in a *BE*:

- i) $U_1(h0) = U_1(hl) = U_1(hh)$; $U_2(h0) < U_2(hl) < U_2(hh)$
- ii) $U_1(h0) > u_{S1}(h0)$
- iii) $U_1(l0) = U_1(ll)$; $U_2(l0) < U_2(ll)$
- iv) $u_{S1}(l0) = u_{S1}(ll)$; $u_{S1}(h0) = u_{S1}(hl) = u_{S1}(hh)$

i) states that the expected payoffs from early adoption is identical for all enthusiasts, but that the option value of waiting is increasing in the a_{\min} .

ii) implies that a stubborn enthusiast will always prefer to adopt early that to wait and adopt then. This follows directly from Lemma A1.

iii) is similar to relation i) – the option value of waiting is higher for uniform followers than for biased followers.

iv) states that adopting in Subgame 1 will be equally profitable for all types with the same a_{\max} .

A.2 Proof of Proposition 1a

A.2.1 Low-adoption BE

We first characterize the low-adoption *BE*. Suppose that adopter i (whose strategies we characterize) (weakly) prefers technology x , i.e. $a^x \geq a^y$ for ease of exposition. We derive equilibrium strategies for each different type assuming that a *BE* exists. In a later step, we derive the conditions for a *BE* to exist.

- **a = (00)**. An adopter of this type trivially will not adopt any technology, i.e. $\sigma_{00}^* = \{0, 0, 0, 0\}$.
- **a = (h0)**. $a_{\min} = 0$, so that there is no incentive to delay, since $\rho_F \geq \rho_2$. Early adoption is assumed to be profitable (if it was not, it would not be for any type and consequently a *BE* would not exist) so that **a = (h0)** implies adoption at $t = 1$, so that we obtain $\sigma_{h0}^* = \{1, 1, 1, 0\}$.
- **a = (10) and a = (11)**. In a *BE*, some types will be strict followers, i.e. they would never adopt unless the other adopter has. This implies that $U_1(ll), U_1(l0), u_{S1}(ll), u_{S1}(l0) < 0$. Since both types have identical $u_{\max} = l$, they will have the same expected (negative) payoffs from adopting without previous adoption in *S1*. Since we assume that $l + b > c$, we obtain the following strategies in a *BE*: $\sigma_{l0}^* = \{0, 0, 1, 0\}$, $\sigma_{ll}^* = \{0, 0, 1, 1\}$.
- **a = (hl) and a = (hh)**. Recall that $U_1(h0) = U_1(hl) > 0$. However, $u_{S3}(hl) > 0$ since $l + b > c$. It is therefore possible that $U_1(hl) \leq U_2(hl)$ even though adopting early would be profitable. Suppose now that an *hl*-type (a biased enthusiast) is indifferent between adopting early and delaying, i.e. $U_1(hl) = U_2(hl)$. This implies $U_1(hh) < U_2(hh)$ since $u_{S3}(hl) < u_{S3}(hh)$, so that $\alpha_{hh}^* = 0$. In a *BE* we have $\alpha_{l0}^* = \alpha_{ll}^* = \beta_{l0}^* = \beta_{ll}^* = 0$. For an *hl*-type to be indifferent between adopting early or late, the following equality must hold:

$$h + \left(\frac{\rho_1}{2} + \rho_F\right)b - c = \left(\left(1 - \frac{\rho_1}{2}\right)h + \frac{\rho_1}{2}l\right) + \left(\rho_1 + \frac{\rho_2}{2}\right)b - c.$$

Inserting the corresponding values for ρ_1 , ρ_2 , and ρ_F and simplifying gives

$$\alpha_{hl}^* = \frac{p(1-p-q)(h-l-b) + \left(\frac{p^2}{2} + q\right)b}{pq(h-l-b) - pqb}.$$

The resulting equilibrium strategies are then $\sigma_{hl}^* = \{\alpha_{hl}^*, 1, 1, 1\}$ and $\sigma_{hl}^* = \{0, 1, 1, 1\}$. ■

A.2.2 High-adoption BE

- The equilibrium strategies for $a = (h0), (l0), (ll), (00)$ are derived analogously to the low-adoption case, i.e. $\sigma_{h0}^* = \{1, 1, 1, 0\}$, $\sigma_{l0}^* = \{0, 0, 1, 0\}$, $\sigma_{ll}^* = \{0, 0, 1, 1\}$, $\sigma_{00}^* = \{0, 0, 0, 0\}$.
- **a = (hl) and a = (hh).** Suppose now that $U_1(hh) = U_2(hh)$ and consequently $U_1(hl) > U_2(hl)$. We know then that $\alpha_{hl}^* = \alpha_{h0}^* = 1$ and $\alpha_{ll}^* = \alpha_{l0}^* = 0$ and find the probability of adopting early by equating $U_1(hh) = U_2(hh)$:

$$h + \left(\frac{\rho_1}{2} + \rho_F\right)b - c = h + \left(\rho_1 + \frac{\rho_2}{2}\right)b - c,$$

which gives the following probability of adoption:

$$\alpha_{hh}^* = \frac{\frac{3}{2}p^2 + q - pq - p}{p^2}$$

We can then characterize the strategies for hl - and hh -types in the high-adoption BE: $\sigma_{hl}^* = \{1, 1, 1, 1\}$, $\sigma_{hh}^* = \{\alpha_{hh}^*, 1, 1, 1\}$. ■

The equilibrium strategies for all types in the high-and low-adoption BE are therefore as follows:

High-Adoption BE

$$\begin{aligned} \sigma_{h0}^* &= \{1, 1, 1, 0\}, \sigma_{hl}^* = \{1, 1, 1, 1\}, \sigma_{hh}^* = \{\alpha_{hh}^*, 1, 1, 1\}, \\ \sigma_{l0}^* &= \{0, 0, 1, 0\}, \sigma_{ll}^* = \{0, 0, 1, 1\}, \sigma_{00}^* = \{0, 0, 0, 0\}. \end{aligned}$$

Low-Adoption BE

$$\begin{aligned} \sigma_{h0}^* &= \{1, 1, 1, 0\}, \sigma_{hl}^* = \{\alpha_{hl}^*, 1, 1, 1\}, \sigma_{hh}^* = \{0, 1, 1, 1\}, \\ \sigma_{l0}^* &= \{0, 0, 1, 0\}, \sigma_{ll}^* = \{0, 0, 1, 1\}, \sigma_{00}^* = \{0, 0, 0, 0\}, \end{aligned}$$

where $\alpha_{hh}^* = \frac{\frac{3}{2}p^2 - pq + q - p}{p^2}$, and $\alpha_{hl}^* = \frac{p(1-p-q)(l+b-h) - \left(\frac{p^2}{2} + q\right)b}{pq(l+b-h) + pqb}$.

A.2.3 Critical Values.

- $\mathbf{a}_{\max} = h$. Consider the high- and low-adoption *BE*. The critical values for early adoption to be profitable are the following:

$$\begin{aligned}\widehat{h}_{high} &= c - \left(p + q - pq - \frac{\alpha_{hh}}{2} p^2 \right) b, \\ \widehat{h}_{low} &= c - (p + q - \alpha_{hl} pq) b, \\ \text{so that } \widehat{h}_{high} &> \widehat{h}_{low}.\end{aligned}$$

Setting $h > \widehat{h}_{high}$ ensures that an h -type will consider adopting at $t = 1$.

- $\mathbf{a}_{\max} = l$. We know that $u_{S1}(l0) = u_{S2}(ll)$, so we can derive one critical value for both types in each scenario. Adopting in Subgame *S1* is profitable if the probability that the other adopter will adopt as well is high enough conditional on her not being an early adopter. This gives us three scenarios, depending on whether $\alpha_{\mathbf{a}} = 1$ or not. This is due to the fact that by observing no adoption at $t = 1$ and moving to Subgame *S1* allows for Bayesian updating if $\alpha_{\mathbf{a}} = 1$ – an adopter cannot be of a type that would have adopted with certainty at $t = 1$ if *S1* is being played. We obtain the following critical values:

$$\text{If } \begin{cases} \alpha_{h0} = \alpha_{hl} = \alpha_{hh} = 1, & \widehat{l}_{high1} = c - \left(\frac{q^2 + 2q(1-p-q)}{2(1-2p(1-\frac{p}{2}))} \right) b \\ \alpha_{h0} = \alpha_{hl} = 1, \alpha_{hh} < 1, & \widehat{l}_{high2} = c - \left(\frac{p^2 + q^2 + 2q(1-p-q)}{2(1-2p(1-p))} \right) b \\ \alpha_{h0} = 1, \alpha_{hl}, \alpha_{hh} < 1, & \widehat{l}_{low} = c - \left(\frac{2pq + p^2 + q^2 + 2q(1-p-q)}{2(1-2p(1-p-q))} \right) b \end{cases}$$

It is easy to show that $\widehat{l}_{high1} < \widehat{l}_{high2} < \widehat{l}_{low}$. If $l < \widehat{l}_{high1}$, $\beta_l = 0$, which ensures the possibility of a *BE*. ■

A.3 Proof of Proposition 1b

As in the previous scenario, $\mathbf{a} = (0)$ will play $\sigma_0^* = \{0, 0, 0, 0\}$.

- $\mathbf{a} = (\mathbf{h})$. For enthusiasts, there is no incentive to delay adoption in a *BE* because $\rho_2 < \rho_F$, and only the highest-valuation type would attempt to start a bandwagon. If therefore expected utility at $t = 1$ is positive,

an adopter with $\mathbf{a} = (h)$ will adopt early, i.e. $\alpha_h^* = 1$. The condition for this is as follows:

$$\begin{aligned} h - c + (p + q)b &\geq 0, \text{ i.e.} \\ h &\geq \tilde{h} \equiv c - (p + q)b. \end{aligned}$$

- $\mathbf{a} = (l)$. Since in a *BE* $\mathbf{a} = (l)$ is the only candidate type for a follower, we need to derive the conditions for this to hold, i.e. $\sigma_l^* = \{0, 0, 1, \cdot\}$.²² Clearly, given $l - c + b > 0$, $\gamma_l^* = 1$. If there has been no adoption at $t = 1$ (*S1*), an adopter will update her belief about the other player. Knowing that $a_{\max} < h$ for the other adopter, an adopter will only adopt at $t = 2$ ($\beta_l^* = 1$) if the following inequality is met.

$$\begin{aligned} l - c + \left(\frac{q}{1-p}\right)b &\geq 0, \text{ i.e.} \\ \tilde{l} &\equiv c - \left(\frac{q}{1-p}\right)b > l. \end{aligned}$$

At $t = 1$, we find that $l - c + (p + q)b \geq l - c + \left(\frac{q}{1-p}\right)b$. Therefore, $\alpha_l^* = 1$ (0) if $l > (\leq) \tilde{l} \equiv c - (p + q)b$. Since $p + q > \frac{q}{1-p}$, $\tilde{l} < \tilde{l}$, so that \tilde{l} is the binding restriction for a *BE* to emerge.

We can then characterize the *BE* in the one-technology case as follows:

$$\sigma_h^* = \{1, 1, 1, 0\}, \sigma_l^* = \{0, 0, 1, 0\}, \sigma_0^* = \{0, 0, 0, 0\}.$$

This is the unique *BE* iff $h > \tilde{h}, \tilde{l} > l > c - b$, where $\tilde{h} = \tilde{l} = c - (p + q)b$. ■

A.4 Proof of Proposition 1c

First note that 0-types will never adopt either technology, i.e. $\sigma_0^* = \{0, 0, 0, 0\}$.

- $\mathbf{a} = (h)$. An h -type will consider adopting early with probability α_h . Payoffs from adopting early or late are $U_1 = h - c + \left(\frac{\alpha_h}{2}p + (1 - \alpha_h)p + q\right)b$

²² δ_l^* is irrelevant in the one-technology case.

and $U_2 = h - c + (\alpha_h p + \frac{1-\alpha_h}{2} p) b$ respectively. Setting $U_1 = U_2$ gives $\alpha_h^* = \frac{1}{2} + \frac{q}{p}$. Simple algebra shows that adopting early will be profitable if $h > \bar{h} = c - (\frac{3}{4}p + \frac{1}{2}q) b$.

- **a = (1)**. As l -types are the only candidates for following, they will play a bandwagon strategy if waiting is preferred to adopting early. This is given if $l < \bar{l}_{high} = c - (p + q) b$ for $\alpha_h^* < 1$ and $l < \bar{l}_{low} = c - (\frac{q}{1-p}) b$ if $\alpha_h^* = 1$.

It is interesting to note that there are two different critical values \bar{l}_{high} , \bar{l}_{low} . These different values come about because if $\alpha_h < 1$, observing no adoption carries no information, i.e. the other adopter can still be an enthusiast playing a mixed strategy. In the other hand, if $\alpha_h = 1$, observing no adoption rules out the possibility of the other adopter being an enthusiast. We summarize the *BE* in the perfect substitutes case:

$$\sigma_h^* = \{\alpha_h^*, 1, 1, 1\}, \sigma_l^* = \{0, 0, 1, 1\}, \sigma_0^* = \{0, 0, 0, 0\},$$

where $\alpha_h^* = \frac{1}{2} + \frac{q}{p}$. A *BE* occurs for the parameter ranges $h > \bar{h}$, $l < \bar{l}_{high}$ if $\alpha_h^* = 1$ and $l < \bar{l}_{low}$ if $\alpha_h^* < 1$, where $\bar{h} = c - (\frac{3}{4}p + \frac{1}{2}q) b$, $\bar{l}_{high} = c - (p + q) b$, and $\bar{l}_{low} = c - (\frac{q}{1-p}) b$. ■

A.5 Proof of Proposition 2

The proposition follows directly from Figure 3. The proof is trivial and therefore omitted. ■

A.6 Proof of Proposition 3

To be completed.

A.7 Proof of Lemma 1

Expected welfare for a single new technology is

$$W_1 = 2p^2 (h - c + b) + 4pq \left(\frac{h+l}{2} - c + b \right) + 2p(1-p-q)(h-c).$$

The expected welfare for two perfectly substitutable technologies is

$$\begin{aligned}
W_S &= 2p^2 \left(h - c + \left(\frac{1}{2} + \alpha_h^* (1 - \alpha_h^*) \right) b \right) + \\
&\quad + 2pq (h - c + \alpha_h^* (l + 2b - c)) + 2p(1 - p - q)(h - c).
\end{aligned}$$

Inspection reveals that for $\alpha_h^* \leq 1$, $\frac{1}{2} + \alpha_h^* (1 - \alpha_h^*) \leq 1$. This implies that expected network benefits are lower in a complete first-period switch (strictly) and a bandwagon switch (weakly) in the two-technology case. ■

A.8 Proof of Proposition 5

If p is sufficiently high, two new technologies will lead to lower aggregate expected welfare than a single one. If p is low and q sufficiently high, two technologies are welfare superior.

The expression for ΔW is as follows:

$$\begin{aligned}
W_U &= 2q(1 - p - q) \cdot \left(p(1 - p) + \frac{\alpha_{hh}^* p^2}{2} \right) (h + l + 2b - 2c) + \\
&\quad + 2q(1 - p - q) \cdot (1 - \alpha_{hh}^*) p^2 (h - c) + \\
&\quad + 2q(1 - p - q) \cdot \left(p(1 - p) + \frac{\alpha_{hh}^* p^2}{2} \right) (h - c) + \\
&\quad + q^2 \cdot (2p(1 - p) + \alpha_{hh}^* p^2) (h + l + 2b - 2c) + \\
&\quad + (1 - p - q)^2 (2p - p^2) (h - c)
\end{aligned}$$

Rearranging, we can see that $\frac{\partial W_U}{\partial \alpha_{hh}^*} > 0$ and $\frac{\partial W_U}{\partial \alpha_{hl}^*} < 0$ for values of $h < l + 2b$, which is given since $h < l + b$. This allows us to study the two extreme cases to derive an upper and lower bound for the welfare changes: $\alpha_{hl}^* = \alpha_{hh}^* = 1$, and $\alpha_{hl}^* = \alpha_{hh}^* = 0$. The corresponding expressions with generic α^* are too complex to analyze.

$$\begin{aligned}
W_U &= 2q(1-p-q) \cdot \left(p(1-p) + \frac{\alpha_{hh}^* p^2}{2} \right) (h+l+2b-2c) + \\
&+ 2q(1-p-q) \cdot (1-\alpha_{hh}^*) p^2 (h-c) + \\
&+ 2q(1-p-q) \cdot \left(p(1-p) + \frac{\alpha_{hh}^* p^2}{2} \right) (h-c) + \\
&+ q^2 \cdot (2p(1-p) + \alpha_{hh}^* p^2) (h+l+2b-2c) + \\
&+ (1-p-q)^2 (2p-p^2) (h-c)
\end{aligned}$$

To be completed.

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