Technology Revolutions in the Presence of Network Externalities

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Abstract

The purpose of this paper is to investigate the effect of varying consumer preferences over technology advance and network size on the timing and frequency of new technology adoption in the presence of installed bases resulting from network externalities. The paper shows that the duration of each adopted technology and the frequency of technology adoptions depend on (a) whether (in consumers' perspectives) the network size effect is a substitute for or a complement to the quality of the technologies; (b) the degree of compatibility of new technologies with the old technology; and (c) the technology growth rate and consumer population size.

Key Words: Technology Revolutions, Technology Adoption, Network Externalities

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1 Introduction

It is widely acknowledged that a radical technology change requires (or, actually is defined by) a complete redesign of the product, its features, and even its function. When facing a technological revolution, the first question that comes to mind is whether the new technology will be adopted given the large installed base of the existing inferior technology.[1] The purpose of this paper is to isolate several major factors affecting the pace at which technological progress occurs. Whereas the literature on technological progress focused on the supply side of new technology providers (e.g., firms' incentives to finance R&D and the effect of patent system), the present paper isolates a major demand side factor affecting the frequency of new technology adoption which is the structure of consumer preferences over technological advance and network sizes supporting of each generation of technologies. The advantage of the using the presently developed demand side approach is that it provides an explanation why some technologies are replaced more often than in others.

This paper identifies several important factors affecting the timing and frequency of new technology adoptions, including

1. consumers' degree of substitution between getting a more advanced technology, and the network size (number of consumers purchasing the technology belonging to the same generation);
2. the technology growth rate and consumer population size;
3. the degree in which a new technology is compatible with the old technology to be replaced.

[1] I am using the term technology revolution to mean an adoption of a new technology. However, Chou and Shy (1993a) distinguish between these two terms. They define technology revolution as the date when firms make the decision to adopt the new technology (while still producing the old technology products) and the technology adoption as the date when consumers actually start purchasing the products based on the new technology. In the present paper, these two dates coincide.

The first item on this list is the primary focus of this paper. Whereas in the literature it is commonly assumed that consumers' utility monotonically increases with both the quality of the technology and the size of the network (number of users), the effect of *varying the degree of substitution* between these two components on the speed of new technology adoption has not been investigated before. I argue that focusing on consumer preferences can help a great deal in understanding (a) why technology is replaced more often in some industries than in others, or alternatively, (b) what type of consumers tend to adopt the new technology based products, and what type of consumers do not switch to the new technology product. Furthermore, I argue that firms, introducing new technology products, should better understand consumer preferences in order to be able to predict whether their new technology product will be adopted or rejected by consumers.

The second item on the above list is important since the technology growth rate and population size affect the benefits new consumers derive from adopting a new technology. The third item on this list is the effect of downward compatibility. The present model is general enough to capture variable compatibility between new and old technologies. This is important since in most cases technological breakthroughs require redesigning the product, and therefore need not be 100 percent downward compatible with the existing technologies. In many cases, the new technology will be completely incompatible with old technologies, whereas some will be only partially compatible (Besen and Leland [1986] provide examples from the broadcasting industry).

The purpose of the present paper is to demonstrate how the structure of consumer preferences affects the speed of new technology adoption. I argue that the degree of substitution between the quality of the technology and the network size has a significant effect on the speed of new technology adoption. More precisely, I show that new technologies are adopted more frequently when consumers treat quality and network size as more substitutable. The reason is that under high substitution, an increase in quality of the technology causes a significant utility increase even if the network size does not change. In contrast, when the degree of substitution is low, an increase in quality does not enhance utility unless the increase in quality is accompanied by an increase in the network size.

Once we establish the importance of consumers' degree of substitution between quality and the network size, it is important to try to motivate the meaning of this substitution effect. When we say that a consumer treats apples and bananas as substitutes, we mean that small price changes cause this consumer to switch from buying apples to buying more bananas (or the other way around). When we say that a consumer treats apples and bananas as complements, we merely mean that the consumer likes to prepare fruit salads (since he or she likes to mix the two fruits). However, what interpretation can be given to the difference between one consumer who treats the quality of the technology and the network size as substitutes and another who treats quality and network size as complements? One way to interpret the degree of substitution between quality and network size is how fast a user (worker) can shift the hardware's task from being performed by a large number of workers (therefore, depending on a high degree of compatibility) "in return" for better hardware performance but with fewer workers assigned to perform this task. Thus, we can think of a high degree of substitution as the flexibility of an office or a company to reorganize work from being decentralized to centralized while maintaining the same efficiency through faster hardware (or a higher quality). Those firms that find it hard to give up decentralization in return for better hardware performance can be regarded as having preferences exhibiting low substitution between quality and network size associated with the hardware they use. Examples for the latter case include slow technology changes in nuclear plants, Cowan (1990), and the slow departure from the Intel based DOS (operating system).

Consider a technology or a product which improves over time. For example, in the computer industry, new and faster chips are introduced very often, however, not every improvement is adopted and marketed. Suppose that the utility of consumers is enhanced by the quality of the technology embodied in the product they purchase and by the number of old and new consumers using the same technology. Then, the newest available technology in each period may not be adopted since new consumers may prefer to use a lower quality product but benefit from a larger network of users (composed of old and young consumers). Using this environment, I analyze the frequency of new technology adoption, and focus on how consumer preferences, consumer population and technology growth rate affect the frequency of new technology adoption.

In the literature, there are several papers analyzing the social and private incentives to adopt a new technology. See for example, Farrell and Saloner (1985, 1986), and Katz and Shapiro (1986). However, these papers do not address the problem how to model the frequency of *repeated* technology adoption, which is the subject of the present paper. Moreover, none of these papers explicitly analyzes the question of how changing the consumers' preferences with respect to the degree of substitution between quality and the gains from larger consumer network affects the speed of adopting new technologies.

The paper is organized as follows. Section 2 develops an infinite horizon consumer overlapping generations model and underlies the "technology" for adopting new technologies as well as consumer preferences. Section 3 illustrates how the speed of technology adoption is determined using two extreme examples where consumers treat the quality of the technology and the network size as (a) perfect complements, and (b) as perfect substitutes. Section 4 generalizes the model to incorporate an arbitrary degree of substitution in consumers' preferences. Section 5 concludes with a discussion of further interpretations and extension possibilities.

2 The model

Consider a discrete time overlapping generations (OLG) economy, where in each period t, $t = 1, 2, \ldots$, the consumer population of the economy consists of two groups of individuals: N_t young consumers of generation $\tau = t$, and N_{t-1} old consumers of generation $\tau = t-1$. I use of the term "generation of consumers" merely for the sake of illustrating a situation where in each period the market consists of entering consumers who have not purchased the product before and a number of consumers who already own the durable product.

I chose to describe the consumer dynamics within an OLG framework for the following reasons: (a) A two-period consumer life is natural for capturing the effects of buying a durable product when young and being "stuck" with it in the second period. (b) The OLG framework is ideal for modeling compatibility of different generations of technologies since each period has a generation of consumers already using an old technology and a new generation of consumers that can potentially adopt a new technology product.

2.1 Technology improvements

We denote by T_t, ($T_t > 0$, $t = 1, 2, 3, \ldots$) the period t quality of the (potential) state-of-the-art technology, and assume that T_t is *exogenously* given and is strictly increasing over time, (i.e., $T_t > T_{t-1}$ for every t). Thus, T_t reflects the ongoing output of an innovation processes which is not modeled in present paper. Since a new technology is not necessarily adopted each period, we denote by V_t the *actual* quality level (stand-alone value) of the period t technology embodied into the product to a period t young who purchases this product. Hence, $V_t \leq T_t$ for all t.

Altogether, the actual technological quality consumed by the young consumers in period t is given by

$$V_t = \begin{cases} T_t & \text{if the young at } t \text{ adopt the new technology} \\ V_{t-1} & \text{otherwise.} \end{cases} \tag{1}$$

Thus, the quality-law-of-motion (1) implies that although technologies (e.g., faster chips) are continuously developed, if no adoption occurs at t, then the quality of the technology does not change compared with period $t-1$. Investment in the context of this paper means spending resources on converting the state-of-the-art technology into actual production. Therefore, as frequently observed, some newly developed chips are not adopted (skipping over technologies is commonly observed).

To each newly adopted technology we attach a "serial" number denoted by g, $g = 1, 2, \ldots$.

Figure 1 illustrates the path of state-of-the-art technology improvements (T_t), the adoption dates of generations g and $g+1$ technologies (t_g and t_{g+1}), and the path of actually adopted technologies (V_t).

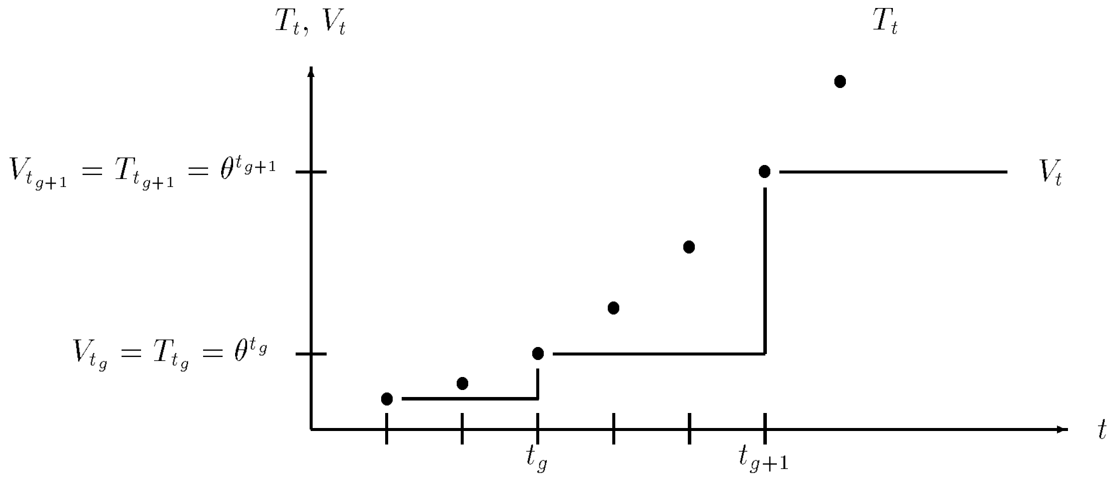

Figure 1: Exogenous technology development path (T_t), and the actually adopted technology path (V_t). *Note:* Figure assumes $T_t \equiv \theta^t$, $\theta > 1$.

The dotted line in Figure 1 is the path of T_t which is the value of the state-of-the-art technology available for adoption at each date t. The solid line illustrates V_t, which is the actual technology available to (the young) consumers at each date t, and t_g and t_{g+1} are two technology adoption dates. At these dates the innovation brings the actual technology (quality) level available to consumers (young) to the state-of-the-art level given by T_t. That is, V_t "jumps" to the level of T_t.[2]

2.2 Innovators and production

We assume that, in each period t, one firm that is endowed with the ability of adopting the state-of-the-art technology given by T_t. With no loss of generality, assume that the

[2]It is assumed that if adoption does not occur for several periods, once adoption is undertaken, the actual technology catches up with the state-of-the-art level. Thus, some technology levels are not utilized since they are never adopted.

investment in technology adoption is costless. We show below, even if adoption if costless, innovators (firms) will frequently find it not profitable to adopt and market newer technology products.

It turns out that our model is general enough to capture a variety of market structures and property rights associated with technology adoption. For example: (a) A persistent monopoly that may offer a new technology whenever it can increase the amount of consumer surplus extracted from incoming consumers. (b) Free entry of potential innovators where a period t innovator (i.e., the agent that adopts the technology) is endowed with a one period patent right that enables her or him to charge a monopoly price in period t only.

2.3 Consumers

Consumers purchase the product only when they are young, and are assumed to gain utility from first period consumption only. We further assume that the utility of each young exhibits network externalities in the sense that utility increases with the number of (old and young) consumers using the same technology. Formally, let c ($0 \leq c \leq 1$) denote the degree in which the new technology is compatible with the old technology (degree of backward compatibility in what follows). In the context of the present model, we interpret the degree c to mean the fraction of old generation consumers that the new technology is compatible with. Thus, if all the young buy an old technology product, then the (effective) number of users of this technology is $N_{t-1} + N_t$. However, if all the young buy a new technology product, then since the new technology is only c-percent compatible with the old technology, the (effective) number of new technology users is equal to $cN_{t-1} + N_t$ (from the point of view of the young at t).[3]

If generation g technology is adopted in period τ, we denote by p^g_τ the price to a young

[3]This definition of partial compatibility is not the only way to interpret the concept of partial compatibility. Chou and Shy (1993b) explicitly define the degree of partial compatibility as the percentage of software packages written specifically for technology A that can run on technology B. Since we do not model software in the present paper, we implicitly assume that percentage of software compatibility translates into percentage of user compatibility.

consumer who purchases the state-of-the-art (generation g) technology in period τ, and by p_τ^{g-1} the period τ price of the older technology (generation $g-1$).

In addition to the stand-alone quality valuation, we assume that the utility of each generation τ *also* increases with the (effective) number of period τ users of the same technology, (network valuation in what follows). Hence, we assume that the utility of a young of generation τ is given by

$$U^\tau = \begin{cases} u(T_\tau, cN_{\tau-1} + N_\tau) - p_\tau^g & \text{if generation } \tau \text{ buys generation } g \text{ technology product} \\ u(V_\tau, N_{\tau-1} + N_\tau) - p_\tau^{g-1} & \text{if generation } \tau \text{ buys generation } g-1 \text{ technology product.} \end{cases} \tag{2}$$

We assume that the function $u(,)$ is monotonically increasing in both arguments (the quality of the technology available at τ, and the effective network size).

2.4 Consumers' consumption choice problem

The problem of each young of generation τ is to choose whether to purchase the product based on the old technology or whether to purchase the product based on the new technology.[4] For given prices of the state-of-the-art technology and the older generation technology, p_τ^g and p_τ^{g-1}, generation $t = \tau$ young consumers would choose to purchase the new technology product if and only if

$$u(T_\tau, cN_{\tau-1} + N_\tau) - p_\tau^g \geq u(V_\tau, N_{\tau-1} + N_\tau) - p_\tau^{g-1}. \tag{3}$$

That is, generation τ chooses the new technology product if the utility from the higher quality product ($T_\tau > V_\tau$) combined with a lower network size ($cN_{\tau-1} + N_\tau \leq N_{\tau-1} + N_\tau$) overtakes the utility from the old technology product.

[4]We disregard a potential coordination problem associated with how all the young manage to choose the same technology. As noted by a referee, whenever a new technology adoption is profitable, the owner of the new technology may be able to lower the price in order to attract the young to purchase the new technology.

2.5 Innovators' technology adoption problem

Subsection 2.2 proposed two market structures under which innovation can be introduced: a persistent monopoly introducing new technologies, or entry of a new firm each period holding a one period patent right for its new technology. In the first case, (3) implies that a monopoly would find it profitable to introduce a new technology in period t if and only if

$$u(T_\tau, cN_{\tau-1} + N_\tau) - u(V_\tau, N_{\tau-1} + N_\tau) \geq 0. \tag{4}$$

That is, if the maximum surplus extracted from new consumers adopting the new technology exceeds the maximum surplus that can be extracted if they adopt the old technology. In the second case, price competition would drive the price of the old technology to zero ($p_t^{g-1} = 0$), and the new technology will be introduced again according to condition (4). Hence, under either market structure:

Proposition 1 *The condition given in (4) constitutes a necessary and sufficient condition for the period t new technology (T_t) to be adopted.*

That is, under both market structures, the new technology will be adopted by the a young generation if and only if the utility gained from the more advanced technology combined with a smaller network size overtakes the utility level associated with the less advanced technology combined with the maximal network level (the sum of the old and young period t consumer population).

Therefore, in view of Proposition 1, for the remainder of this paper we can ignore the firms' side and focus the entire analysis on the *adoption condition* given in (4).

2.6 Measuring the duration of technologies and the frequency of new technology adoption

We now introduce the notation for measuring the length of time that a technology lasts which we call the *duration* of a generation of technologies. Then, we determine the frequency of new technology adoptions.

We first approximate the duration of generation g technology by a real number d_g, where d_g is determined by the implicit condition

$$u(T_{t_g+d_g}, cN_{t_g+d_g-1} + N_{t_g+d_g}) = u(T_{t_g}, N_{t_g+d_g-1} + N_{t_g+d_g}). \tag{5}$$

That is, in view of the adoption condition (4), the real approximation of the duration of generation g technology, d_g, is the duration that makes the utility of a young, evaluated at the potentially available new technology level at the last date of generation g technology ($t = t_g + d_g$) and the appropriate network level, overtake the utility of the young evaluated at the old technology and full network size.

Since our model is formulated in discrete time, we need to make the following definition:

DEFINITION 1

1. *The* **duration** *of generation g technology, denoted by Δ_g, is defined by*

$$\Delta_g \equiv \lceil d_g \rceil$$

   where $\lceil d_g \rceil$ is the smallest integer greater or equal to d_g.

2. *The* **frequency** *of introduction of new technologies evaluated at the introduction date of genration $g+1$, denoted by f_g, is defined by $f_g \equiv 1/\Delta_g$.*

For example, if $d_g = 4.2$, then $\lceil d_g \rceil = 5$, meaning that the generation g technology lasted for five periods before it is replaced by generation $g+1$ technology.

The following proposition provides simple predictions about the timing and frequency of technology changes even without assuming particular utility functions:

Proposition 2 *If new technologies are 100-percent compatible with old technologies, then new technologies are adopted each period, hence, each technology lasts for exactly one period. Formally, if $c = 1$, then $\Delta_g = f_g = 1$ for all $g = 1, 2, \ldots$.*

Proof. Since the function u is nondecreasing, $c = 1$, and $T_t > T_{t-1}$ for every t, then

$$u(T_t, N_{t-1} + N_t) \geq u(T_{t-1}, N_{t-1} + N_t), \quad \text{for all } t.$$

Q.E.D.

3 Substitutability Between Technological Advance and Network Size: Two extreme examples

We now turn to investigating how the degree of substitution between technological advance and network size affects the duration of each technology and frequency of technology changes. In this section we investigate this effect by focusing on two extreme cases: the two components are either perfect complements or perfect substitutes. These cases highlight all the intuition behind the adoption of new technologies while keeping the analysis very simple and mainly graphical. Section 4 generalizes the present analysis to arbitrary degrees of substitution in consumers' preference.

3.1 An example for the case of complements

Consider the preferences for *perfect complements* given by[5]

$$U^\tau = \begin{cases} \min\{V_\tau; N_{\tau-1} + N_\tau\} & \text{if generation } \tau \text{ purchases an old technology product} \\ \min\{T_\tau; cN_{\tau-1} + N_\tau\} & \text{if generation } \tau \text{ purchases the new technology product.} \end{cases} \tag{6}$$

Figure 2 illustrates the indifference curves generated by the utility function (6), in the network-quality (N, T) space.

Figures 2a illustrates the case where $c = 1$ meaning that the new technologies are 100-percent compatible with older technologies, and confirms Proposition 2 where under 100-percent compatibility between new and old technologies, new technologies are always adopted

[5]Following Proposition 1, we can present our analysis without specifying prices in consumers' utility functions.

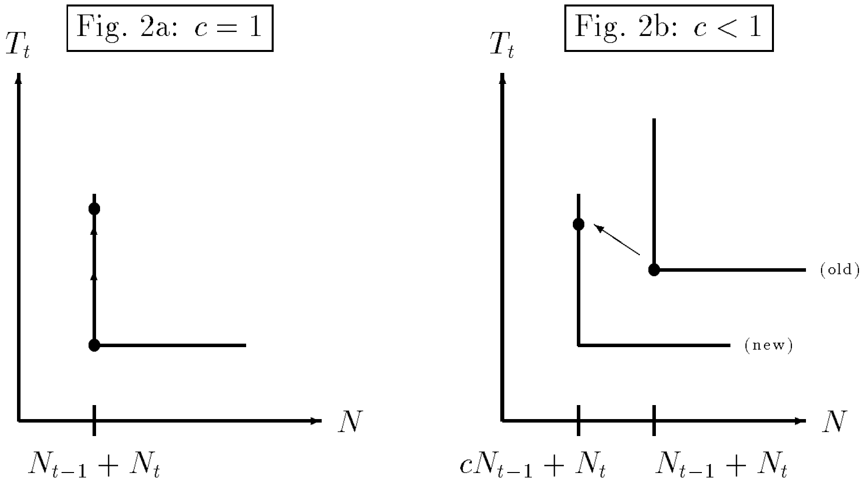

Figure 2: Perfect complements

since adoption places the young on a higher indifference curve (well, only in the case of perfect complements, on the same indifference curve).

Figure 2b illustrates the case $c < 1$, where new technologies are less than 100-percent compatible with the older technologies. In this case, new technologies will never be adopted even if the technology growth rate is very high. This happens since when the network and technology levels are perfect complements, technology growth cannot be "enjoyed" by the young because the adoption of a new technology is associated with a drop in the network size.[6]

3.2 An example for the case of substitutes

Consider the widely used linear preferences given by

$$U^\tau = \begin{cases} V_\tau + N_{\tau-1} + N_\tau & \text{if generation } \tau \text{ purchases an old technology product} \\ T_\tau + cN_{\tau-1} + N_\tau & \text{if generation } \tau \text{ purchases the new technology product.} \end{cases} \tag{7}$$

[6]Figure 2 assumes that the initial technology-network pair (T_t, N) lies "above the diagonal," meaning that $T_t > N_{t-1} + N_t$. When this inequality is reversed, so (T_t, N) lies "below the diagonal," new technologies may get adopted since adoption may place consumers on a higher indifference curve.

Figure 3 illustrates the indifference curves generated by the utility function (7), in the network-quality (N, T) space.

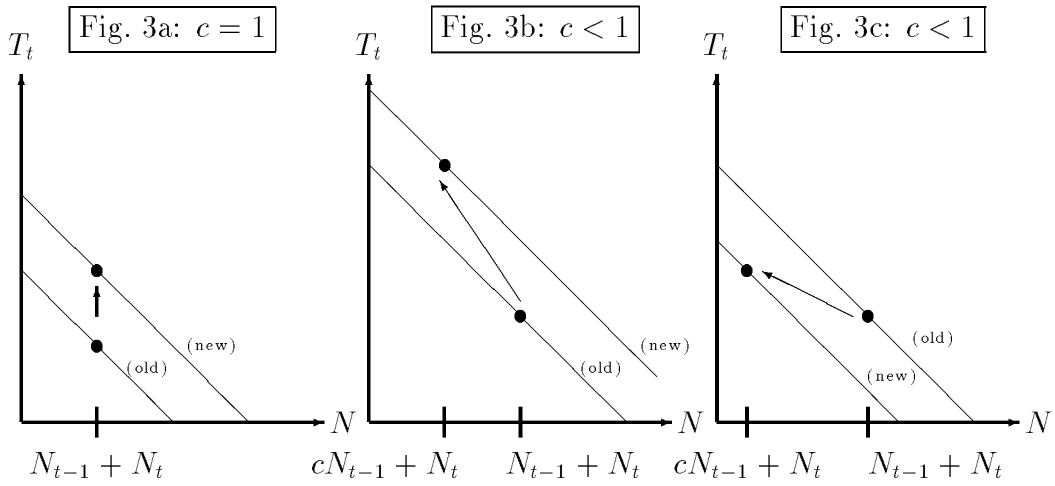

Figure 3: Perfect substitutes

Figures 3a illustrates case where $c = 1$ meaning that the new technologies are 100-percent compatible with older technologies, and confirms Proposition 2 where under compatibility between new and old technologies, new technologies are always adopted since adoption places the young on a higher indifference curve.

Figures 3b and 3c are associated with $c < 1$ where new technologies are less than 100-percent compatible with the older technologies. In contrast to Figure 2b, Figure 3b illustrates how under perfect substitution consumers may benefit from adopting new technologies even when the new technologies are not 100-percent downward compatible, which demonstrates our main point, to be developed in section 4, that a higher degree of substitution in consumer preferences generates more frequent new technology adoption.

Figure 3c illustrates that even under perfect substitution, a new technology may not get adopted if the quality improvement is not sufficiently high and/or the degree of compatibility between the new and the older technology is low.

We summarize the analyses of subsections 3.1 and 3.2 with the following proposition:

Proposition 3 *Whenever new technologies are not 100-percent compatible with older technologies, new technologies are never adopted if consumers treat network size and technological advance as perfect complements, but may be adopted if consumers treat them as perfect substitutes.*

Proposition 3 hints that faster adoption of new technologies is likely to observed in industries (economies) where consumers treat the network size and technology advance as substitutes rather than as complements.

4 A General Model of Technology Adoption

Section 3, demonstrated two extreme cases in which consumers treat the network size and technology advance as perfect complements or as perfect substitutes. This section generalizes consumers' preferences to arbitrary degrees of substitution.

The CES (constant elasticity of substitution) utility function given below yields the utility functions (6) and (7) as special cases. For $-\infty < \alpha \le 1$ define

$$U^\tau \equiv \begin{cases} [(V_\tau)^\alpha + (N_{\tau-1} + N_\tau)^\alpha]^{1/\alpha} & \text{if generation } \tau \text{ purchases an old technology product} \\ [(T_\tau)^\alpha + (cN_{\tau-1} + N_\tau)^\alpha]^{1/\alpha} & \text{if generation } \tau \text{ purchases the new technology product.} \end{cases} \tag{8}$$

The features of the CES utility function can be easily seen by calculating how a change in the parameter α affects the slope of the indifference curves defined by

$$MRS_{T,N}(T,N) \equiv -\frac{\partial U(T,N)}{\partial N} \Big/ \frac{\partial U(T,N)}{\partial T}.$$

Therefore,

$$MRS_{T,N} = -\frac{N^{\alpha-1}}{T^{\alpha-1}}, \text{ hence, } \frac{\partial MRS}{\partial \alpha} = e^{(1-\alpha)[\ln(T)-\ln(N)]}[\ln(T) - \ln(N)]. \tag{9}$$

It follows from (9) that $\frac{\partial MRS}{\partial \alpha} \geq 0$ if and only if $T \geq N$. Hence, as α decreases, the slope of the indifference curves becomes steeper when $T > N$ and flatter when $T < N$. In the limit as $\alpha \to -\infty$, the indifference curves become L-shaped. Note that the slope equals -1 when $T = N$ (on the diagonal). Altogether, as α increases, the indifference curves become flatter in the (N, T) space implying that in the limit, when $\alpha = 1$, the two components become perfect substitutes, see equation (7). In contrast, when α declines to $-\infty$, the two components become perfect complements, see equation (6). All these cases are illustrated in Figure 4.

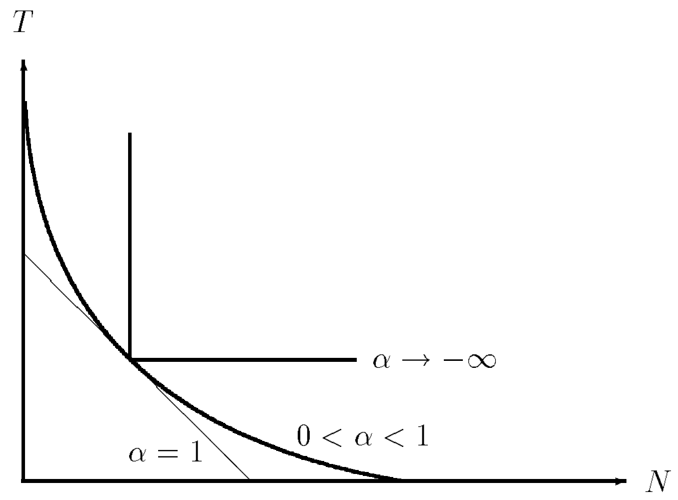

Figure 4: Indifference curves generated by a CES utility function

I assume that technology advance progresses exponentially according to the law of motion given by

$$T_t = \theta^t, \quad \theta > 1, \tag{10}$$

where the parameter θ measures (one plus) the rate of potential product improvement, see Figure 1. Also, assume that the number of new consumers entering each period follows the law of motion given by

$$N_t = \eta N_{t-1} = \eta^t N_0, \quad \eta > 0. \tag{11}$$

Thus, if $\eta > 1$ the consumer population is growing over time. If $\eta < 1$ the consumer population is declining with time, and if $\eta = 1$, the consumer population is constant so each period the same number of N_0 consumers enter (and exit) the market.

Substituting (10) into (1), then into (8), and then into (5) yields

$$\left(\theta^{t_g+d_g}\right)^{\alpha} + \left(cN_{t_g+d_g-1} + N_{t_g+d_g}\right)^{\alpha} = \left(\theta^{t_g}\right)^{\alpha} + \left(N_{t_g+d_g-1} + N_{t_g+d_g}\right)^{\alpha}.$$

Substituting (11), after factorization we have that

$$\left(\theta^{t_g}\right)^{\alpha}\left[\left(\theta^{d_g}\right)^{\alpha} - 1\right] = \left(\eta^{t_g+d_g-1}\right)^{\alpha}(N_0)^{\alpha}[(1+\eta)^{\alpha} - (c+\eta)^{\alpha}]. \tag{12}$$

Thus, after technology g is adopted, as time progresses (d_g increases), a new technology is adopted whenever the left-hand-side of (12) overtakes the right-hand-side of (12). From (12) one can solve for d_g which approximates the duration of each technology.

In what follows, I investigate how the frequency of technology adoption and the duration of technologies are affected by changing the consumer population size, degree of downward compatibility between new and older technologies, and the degree of substitution in consumer preferences. I will use the following terminology:

DEFINITION 2 *We say that technologies have* **shorter durations** *if d_g decreases for some technologies and does not increase for others. In this case, we also say the frequency of new technology adoption has increased. We say that new technology adoption is* **continuous** *if a new technology is adopted each period, i.e., $d_g \leq 1$.*

I now examine how the initial consumer population size, measured by N_0, affects the frequency of new technology adoption. Note that an increase in N_0 implies a proportional increase in each period's consumer population. However, it immediately follows from (12) that an increase in N_0 must decrease d_g. Hence,

Proposition 4 *An increase in the initial consumer population size will increase the duration of each generation of technologies and will therefore reduce the frequency of new technology adoption.*

Proposition 4 merely states that independently of whether the population is increasing or decreasing over time, an increase in the initial consumer population size, hence, the consumer population in each period, will intensify the network effect in a young consumer's preferences and will therefore slow down the frequency of adopting new technologies that are less than 100-percent compatible with the older technology.

I now examine how the degree of downward compatibility between a new technology and the old technology, measured by the parameter $0 \leq c \leq 1$, affects the frequency of new technology adoption. Equation (12) implies that an increase in c must decrease d_g. Hence,

Proposition 5 *An increase in the degree of downward compatibility between new and old technologies would decrease the duration of each technology and would therefore increase the frequency of new technology adoption. Formally, an increase in c would decrease d_g.*

As expected, Propositions 4 and 5 imply that the initial consumer population size, N_0, and the degree of backward compatibility, c, are the causes of the "lock-in" effect described in Arthur (1989).

I conclude by investigating how varying the degree of substitution between technological advance and network size affects the frequency of technology adoption. To further simplify the analysis, I assume that the consumer population is constant over time, that is, $\eta = N_0 = 1$. The following proposition extends Proposition 3.

Proposition 6 *Under constant consumer population, for technology growth rates exceeding a certain threshold value, an increase in the degree of substitution will shorten the duration of technologies. Formally, for $\eta = N_0 = 1$, there exists $\hat{\theta}$ such that for every $\theta \geq \hat{\theta}$, an increase in α will reduce d_g.*

Proof. Condition (12) can be written as

$$F(\alpha, d_g) \equiv \theta^{\alpha(t_g+d_g)} - \theta^{\alpha t_g} - 2^\alpha + (c+1)^\alpha = 0. \tag{13}$$

By the implicit-function theorem, $\frac{\partial d_g}{\partial \alpha} = -\frac{\partial F}{\partial \alpha} \Big/ \frac{\partial F}{\partial d_g}$. Clearly, since $\theta > 1$, $\partial F / \partial d_g > 0$. Next,

$$\frac{\partial F}{\partial \alpha} = \theta^{\alpha t_g} \ln[\theta] \{\theta^{\alpha d_g}(t_g + d_g) - t_g\} - 2^\alpha \ln[2] + (c+1)^\alpha \ln[c+1],$$

which is positive for sufficiently high values of θ; in this case $\frac{\partial d_g}{\partial \alpha} < 0$. *Q.E.D.*

Note that the restriction on θ to exceed a certain threshold value is needed to ensure that new technology adoption is welfare improving (given partial backward compatibility). This restriction is similar to the restriction we placed on the variables in Figure 2 to lie "above the diagonal" meaning that the technology level is sufficiently advanced.

5 Discussion

The main result of the present paper can be interpreted in two ways: First, products in which consumers value quality and network size as substitutes tend to be improved more frequently than others. Second, for a given product, an improved technology will be adopted by the consumers that treat quality and network as substitutes and rejected by those who treat the two components as complements. Between these two interpretations, I find the second interpretation more appealing simply because preferences should be interpreted as consumer specific rather than as product specific. Therefore, the second interpretation of our main result would be that when a new technology is introduced, the market for the product splits between two types of consumers: those who treat the two components as substitutes (high α in (8)) and therefore adopt the new technology; and those who treat the two components as complements (low α) and do not adopt the new technology. Thus, the hypothesis generated by this result is that those consumers who "deserted" the DOS (operating system) and adopted more advanced operating systems treated the two components as substitutes, while those who never left the DOS treat the two components as complements. This discussion implies that the model can be extended to incorporate heterogeneous consumers entering in each period. Thus, in each period the young will split into two groups according to their degree of quality-network substitution: those who buy the old technology and those who buy the newest technology.

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