Innovations and technological comebacks*

Renaud Foucart†

Cheng Wan‡

Shidong Wang§

Abstract

Motivated by the comeback of the vinyl, we explore the idea that the success of a third-generation technology (digital music) can have adverse effects on the second generation (CD) but positive effects on the first one (vinyl). This phenomenon arises in a market if the process of innovation is not transitive. In particular, we identify a condition such that the second generation completely substitutes the first one, the third generation completely substitutes the second one, but the first and the third generations have enough complementarities to coexist. Beyond the case of music industry, our model has implications on product positioning and product design.

Keywords. brand rejuvenation, comeback, product positioning, product design

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†*Email:* renaud.foucart@gmail.com, Institute for Management, Humboldt University, Berlin

‡Corresponding author. *Email:* cheng.wan.2005@polytechnique.org, School of Public Economics and Administration, Shanghai University of Finance and Economics

§*Email:* shidong.wang@regents.ox.ac.uk, Oxford Prospects and Global Development Centre. S. Wang is supported by a EPSRC Grant EP/I01361X/1 at the University of Oxford

1 Introduction

The process of innovation is traditionally seen as one where a new (and better) product or technology replaces an outdated standard. However, examples abound where different generations coexist, and sometimes obsolete technologies become useful again, especially in combination with a newer one. A very timely example is the "comeback of vinyl." While this technology had been almost abandoned in the late nineties, vinyl sales have been constantly increasing since the early 2000s. Engineers even predict that, while remaining a niche product, vinyl record has come back to stay as the only analogue medium (Bartmanski and Woodward, 2015).

The purpose of this paper is to offer a theoretical framework for the study of a feature of innovation which has been largely overlooked: the process of substitution by subsequent innovations is not necessarily transitive. The fact that a second-generation product or technology makes first-generation ones obsolete does not impede the success of the third generation to have positive effects on the first one. The arrival of the third generation can indeed create new complementarities with the first one, that make a comeback possible. Our work is at the intersection of the literature on product positioning and design and the one on innovation and technology substitution. By understanding better incomplete substitutions, we claim to identify conditions on product positioning and design that make the comeback of technologies possible. We use the word "technology" in a broad sense: our specification applies to durable goods for which different variants appear sequentially, the next one being preferred to the previous one, all other things held equal.

We provide a simple, testable condition on consumer choice for the process of technology substitution not to be transitive. A second generation (CD) can be better than a first generation (vinyl) in most dimensions, while the remaining disadvantages are tolerable, so that no consumer bothers owning both of them. The same may hold between the third generation (digital music) and the second one. However, it is still possible that there is one dimension on which the advantages of the first generation compared with the third one are sufficiently important for the former to complement the latter. For instance, the physical features of the vinyl make it an ideal complement to digital music for consumers valuing this dimension. In general, a given consumer that would completely stop buying the first generation when the second appears may start buying the first generation again as a complement to the third one, if its “strong” characteristics add enough value. The above condition is at the consumer level. It is absolutely possible that it only applies to a subset of the population, so that some consumers never stop buying vinyl while others do not see the interest of vinyl in presence of digital music. The “three-generation” model is a minimum working example, and there is no particular reason to limit our understanding of incomplete substitution to a specific number of innovations. More generally, our model shows in which circumstances a product that has been abandoned by a given type of consumers can become attractive again in the presence of an innovation.

As documented at length in the marketing literature, consumer choice is a complex decision based on several dimensions of product positioning and product design (see for instance Green and Krieger, 1992; Kaul and Rao, 1995), which, in turn, aim at heterogeneous consumers (see for instance Michalek et al., 2011). In particular, if consumers value different attributes of a product in different ways, whether because they have different preferences or because they happen to be in different situations, a large part of the job of the marketer is to decide which product attributes to emphasize (Chakraborty and Harbaugh, 2014). The marketer also needs to choose whether to design and advertise the product as mainstream or to aim at a specific niche of the market (Johnson and Myatt, 2006). We show that if marketers are to rejuvenate an obsolete technology, they may achieve it by emphasizing those attributes that some consumers value in the first generation as a complement to the third one. If the conditions for a comeback are relatively difficult to meet, a marketer should choose a “niche” design in order to provide enough added-utility for some consumers to choose an additional “coming-back” technology. If the comeback is easier to achieve, the marketer should choose a “mainstream” design. As discussed in Section 7, our approach is not limited to the clear-cut examples where the coming-back technology is almost identical to what it used to be, but also to brand rejuvenation with strategic use of some characteristics of abandoned technologies.

Extensive research in business and economics has been carried out on the diffusion of innovation, with the aim of understanding the diffusion of new technologies over the course of industrial history (Griliches, 1960, Geroski, 2000, Young, 2009, Peres et al., 2010). For example, market analysts wish to predict and further influence how a new product gradually occupies the market or how old ones vanish from it (Mahajan and Muller, 1979, Mahajan et al., 1990, Chandrasekaran and Tellis, 2007). More recent models have studied simultaneous launches and coexistence of technologies (see for instance Libai et al., 2009, and Guseo and Mortarino, 2014), including applications to music industry (Guidolin and Guseo, 2015). The role of social networks and word-of-mouth in the adoption of new products has also been the subject of a lot of attention (Trusov et al., 2009, Moldovan et al., 2011). However, none of these models studies conditions for a fading technology to come back. Therefore, our approach provides a micro-foundation for such models to integrate the possibility of non-transitive substitutions.

In the next section, we describe in more details the comeback of vinyl, and why it satisfies the conditions we identify for a technological comeback with time independent preferences. Section 3 presents a simple consumer-choice framework to understand technological comebacks. We solve for a specific example with utility function linear in product attributes in Section 4. Section 5 provides a general condition on technological comebacks. We study product design in Section 6. Finally, we discuss some implications of our results to marketing and conclude in Section 7.

2 The vinyl comeback: facts and data

According to Nielsen Soundscan, more than 9.2 million vinyl records were sold in the U.S. in 2014. This marks a 52% increase over the year before, the largest number recorded by SoundScan since the music industry monitor started tracking them back in 1991.[1] Depending on the sources, this represents around 5[2] or 6[3] percent of the total album sales recorded on a year. A figure that some argue to be largely undervalued.[4] These days,

[1]Megan Gibson, "Here's Why Music Lovers Are Turning to Vinyl and Dropping Digital," The Time, January 13, 2015

[2]See Megan Gibson, "Here's Why Music Lovers Are Turning to Vinyl and Dropping Digital," The Time, January 13, 2015

[3]See Hanna Ellis Pettersen, "Record sales: vinyl hits 25-year high," The Guardian, January 3, 2017 and the date from the RIAA.

[4]"LPs, unlike CDs, are a one-way sale: labels do not accept returns of unsold copies. Therefore labels and retailers are careful to order only what they think they can sell. Moreover, LP jackets do not consistently carry bar codes (...) and therefore cannot be scanned at the cash register. And many shops that sell LPs are independents that do not report their sales.", in Allan Kozinn, "Weaned on CDs, They're Reaching for Vinyl," The New York Times, June 9, 2013

every major label and many smaller ones are releasing vinyl. Most new major releases have a vinyl version.[5] The majority of buyers of vinyl are 35 years old or younger.[6]

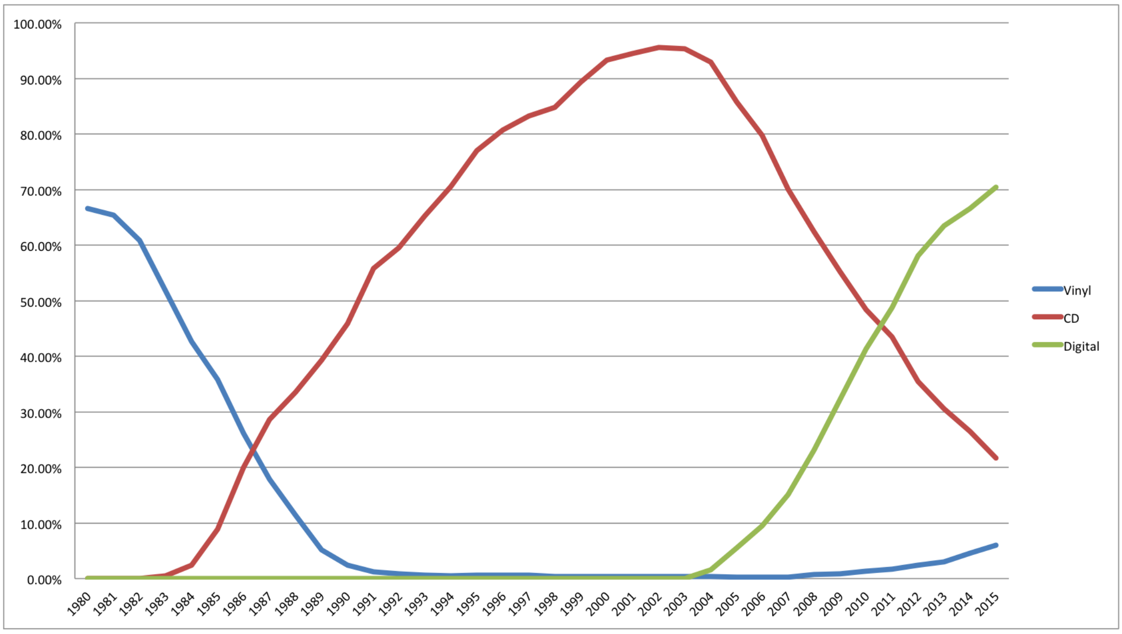

Figure 1: Market share of different music technologies since 1980 (in terms of total revenues in the US). Source: RIAA and authors' computations.

We present in Figure 1 the respective shares of vinyl, CD and digital sales in the US since 1980, according to the public data from the website of the RIAA. One can observe a three-generation substitution pattern, very similar to a classic substitution model, with the exception of a niche comeback. The second generation (CD) almost entirely replaces the first one (vinyl). A third generation (digital) substitutes the second one (CD). The comeback of the first happens only in the presence of the third. We do not distinguish between digital sales and streaming services, which could arguably be considered as different technologies. Indeed, the latter are sometimes seen as a fourth generation technology competing with the former (see Wlömert and Papies, 2016).

If at least some consumers with stable preferences start buying vinyl again only when digital music is available, the condition we identify in the model of non-transitive innovation is fulfilled. A comeback in which the condition is not fulfilled would also be possible if all consumers have changed preferences and become nostalgic of vinyl: if the

[5] Allan Kozinn, "Weaned on CDs, They're Reaching for Vinyl," The New York Times, June 9, 2013

[6] Reported in Ben Sisario, "Vinyl LP Frenzy Brings Record-Pressing Machines Back to Life," the New York Times, September 14, 2015.

perceived value of vinyl increases, it is trivial that more consumers buy it. An explanation exclusively based on nostalgia, understood as a change in consumers' preferences, would however contradict a number of studies in psychology, sociology and anthropology. Such studies show that it is precisely because music has become mostly dematerialized that more and more consumers buy new albums in what they perceive to be the most tangible format: vinyl (Magaudda, 2011, Bartmanski and Woodward, 2015, Negus, 2015). Analysts do seem to agree on one thing: the success of the vinyl is due to the fact that "Records are admirably physical, the antithesis of the everywhere-and-nowhere airiness of *the cloud*," and that high involvement in – mostly digital – music is connected to a perception of tangible records as more valuable (Styvén, 2010).

In this paper, we offer a framework based on time-independent preferences to explain the trend identified above. While we do not rule out the role of nostalgia in consumer choice (see also Section 7.1), we show that a change in consumers' preferences is not necessary to explain technological comebacks.

3 A model of sequential technologies

A natural explanation of a consumer's willingness to possess simultaneously more than one technology with similar functions is that they are imperfect substitutes to each other in different situations in life. A consumer chooses to own one or several technologies, and she incurs a fixed cost for each additional one. While our specification is pretty general, an important assumption is that a technology is a durable good, so that using a given technology in all situations is not more costly than using it in one situation only.

There are I consumers and S states of the world. The set of consumers and that of states are denoted by $I = \{1,\dots,I\}$ and $S = \{1,\dots,S\}$ respectively. States represent different situations. State s arises with known probability π_{is} to consumer $i \in I$, with $\sum_{s\in S}\pi_{is} = 1$. The distribution of states is heterogeneous among the consumers. In the musical context, the state can correspond to the location (at home, in a car, on a train, in the street) or the mood in which the consumer is when the music consumption takes place.

Let $L = \{1,\dots,L\}$ be the set of L available technologies, each of them being valued over N attributes in the set $N = \{1,\dots,N\}$. Vector $v_l = (v_{ln})_{n\in N}$ denotes the score of technology $l \in L$ over each attribute. The utility of technology l conditional on being in state s is $u_s(v_l)$, with u_s weakly increasing in all elements of v_l and strictly increasing in at least one element of v_l. Utility weakly increasing in each characteristic is the standard assumption of monotonicity, according to which no one dislikes that a product turns better in one dimension. Strict monotonicity in at least one dimension rules out the trivial case where the consumer is indifferent between all possible products. Such a specification represents the fact that consumers abstract several pieces of information on product characteristics and marketing mix variables into a small number of perceptual attributes (Kaul and Rao, 1995). For expositional simplicity, we assume that π_{is} fully determines the heterogeneity among consumers. However, all our results hold with consumer-specific utility functions – i.e., consumers not only differ on how frequently they are in different states, but also how they value each dimension in each state (we use such a formulation in Section 6). Since we solve each condition for a consumer i, consumer-specific utility functions simply correspond to adding a subscript i below each u function, so that one would have u_{is} instead of u_s.

We assume that consumers maximize their expected utility and always buy at least one technology (the outside option is sufficiently low). To simplify the exposition, we normalize the price of each additional technology to p, and we assume utility to be linear in p. This implies that the market for the provision of the technologies is competitive. The assumption of a single price p for all technologies is for expositional simplicity only. It is easy (see Appendix) to generalize the results to different prices. We further assume a zero marginal cost of using the technology. This corresponds to our assumption of technologies being durable goods. However, assuming a small marginal cost would not affect our results qualitatively. The higher the marginal cost, the more a consumer is willing to buy more than one technology — because there is no benefit from using the same in all states of the world. In the extreme, if technology is a non-durable good consumed only once, the "best" product is bought in each state of the world.

Define by $\Lambda_i \subset L$ the set of technologies in the bundle bought by consumer i. Then her expected utility is

$$f_i(\Lambda_i) = \sum_{s \in S} \pi_{is} \max_{l \in \Lambda_i} u_s(v_l) - p|\Lambda_i|. \tag{1}$$

The first part of equation (1), $\sum_{s\in S} \pi_{is} \max_{l\in\Lambda_i} u_s(v_l)$, is the expected value of a technological bundle Λ_i. Remark that in each state of the world, the "best" technology in the bundle for that state is used. The second part of the equation is the cost of possessing this bundle: $p|\Lambda_i|$, where $|\Lambda_i|$ denotes the number of technologies in the bundle chosen by consumer i. The cost of each technology is paid once and for all, regardless of how often it is used.

Her optimal bundle Λ_i^* solves

$$\Lambda_i^* = \arg\max_{\Lambda_i \subset L} f_i(\Lambda_i).$$

In other words, a consumer chooses such a bundle of technologies that no additional technology can bring enough added-utility in some situation to justify the cost of owning it. For reference, we summarize the key notation in Table 1.

Table 1: Key notation

Symbol	**Interpretation**
π_{is}	Probability for a consumer i to be in state s, only source of heterogeneity in the main model
v_{ln}	Score of technology l on attribute n, aggregated in vector v_l
$u_s(v_l)$	Utility from technology l in state s, increasing in each element of v_l, strictly increasing in at least one element v_{ln}
p	Normalized price of owning a technology, strictly higher than zero

4 Example

Following Chakraborty and Harbaugh (2014), consider a simple, special case where utility $u_s(v_l)$ of a technology l is multi-linear in the scores v_{ln}'s of the product attributes n's, at each state s. This assumption is for simplicity only. We go back to more general utility functions for technologies when deriving the results in the next section. To rule out the trivial case where all consumers buy all technologies, we consider the case in which the cost of an additional technology p is strictly positive.

In addition, suppose in this special case that there are two states of the world ($s = 1,2$) and two product attributes ($n = 1,2$). Therefore, the vector of attributes of technology l is $v_l = (v_{l1}, v_{l2})$. The utility functions u_s's of a technology l in state 1 and state 2 – identical for all consumers in this example – are respectively

$$u_1(v_l) = \alpha v_{l1} + (1-\alpha)v_{l2}, \quad u_2(v_l) = \alpha v_{l2} + (1-\alpha)v_{l1}.$$

The value of parameter α specifies how the attributes weigh differently in the two states. For example, if $\alpha = \frac{1}{2}$, then both attributes are equally valued in each of the states, and the two states are equivalent. On the contrary, if $\alpha = 1$, then only one attribute matters in each state. These are two extreme cases. Here we consider the intermediate case where the two attributes are both valued, but with different weights, in each of the states. Without loss of generality, assume $\frac{1}{2} < \alpha < 1$, i.e. attribute s matters more in state s, for $s = 1,2$. In other words, in state 1, the most important attribute of the product is attribute 1, while in state 2 it is attribute 2. In the context of musical industry, for example, state 1 can correspond to a state of the world where consumers care more about the practical aspects of the technologies, while in state 2 they care more about the object itself.

Let the product attributes $n = 1,2$ be respectively "usability" and "object" with scores displayed in Table 2 for three generations of technologies.

Table 2: Example of scores of technology attributes v_{ln}

Technology/Attribute	**usability** ($n = 1$)	**object** ($n = 2$)
Vinyl ($l = 1$)	1	3
CD ($l = 2$)	2	2
Digital (l=3)	3	1

Let $EU_i(v_l)$ denote the expected utility of technology l for consumer i if she consumes it in all the states,

$$EU_i(v_l) = \pi_{i1}u_1(v_l) + \pi_{i2}u_2(v_l).$$

Comparing the three generations of technologies, we can show that, for each consumer who is more likely to be in state 1 one has:

$$EU_i(v_3) > EU_i(v_2) > EU_i(v_1).$$

It is also clear from Table 2 that no technology is better than another in both states of the world.

First, consider the case in which only the first two technologies are available: $L = \{1,2\}$. Since $EU(v_2) > EU(v_1)$, if a unique technology is chosen, it is the second one (CD). It is possible to show (see (5) in the proof of Proposition 1) that a consumer i buys the first generation (vinyl) as a complement, when the second generation (CD) is available, if and only if the probability of being in state 1 π_{i1} is smaller than a threshold $\tilde{\pi}_{i1}$. The expected value of the additional benefit of owning a vinyl when the state of the world is 2 (when the object matters more) must be higher than the additional cost of owning a second technology p, and this happens only if the frequency of state 2 is high. Hence, if π_{i2} is big enough, the optimal bundle that maximizes (11) is $\Lambda^* = \{1,2\}$, and otherwise the optimal bundle is $\Lambda^* = \{2\}$.

Second, consider the case in which only the last two technologies are available: $L = \{2,3\}$. In Table 2, the difference between the scores of digital and CD is the same as that between the scores of CD and vinyl for each attribute. Due to the multi-linearity of u_s's, the condition to buy both CD and digital music when only those two are available is also that π_{i1} must be smaller than $\tilde{\pi}_{i1}$. Hence, a consumer that completely substitutes CD to vinyl also completely substitutes digital music to CD.

Finally, if the three technologies are available: $L = \{1,2,3\}$, the condition for the coexistence of vinyl and digital is fulfilled if and only if (cf. (8) in the proof of Proposition 1 in Appendix) π_{i1} is smaller than a threshold $\hat{\pi}_{i1}$, which is higher than $\tilde{\pi}_{i1}$. The reason is that the difference between the scores of vinyl and digital on the "object" attribute is twice as large as the difference between those scores of vinyl and CD or between those scores of CD and digital on this attribute. Hence, a consumer that would completely stop buying vinyl when CD appears may still choose to combine vinyl and digital music.

We show in Figure 2 the possible patterns of substitution for a consumer i with $\pi_{i1} > \frac{1}{2}$, when the technologies of three generations successively appear and each of them is better than the previous one in the sense that it provides higher expected utility $EU_i(v_l)$, at a common cost $p = \frac{1}{5}$. The first area on the top left part of the graph corresponds to cases $\pi_{i1} > \hat{\pi}_{i1}$ in which the probability of being in the most frequent state of the world is high (high π_{i1}) and/or in which the importance attached to each product attribute is quite similar in different states of the world (low α). In this case, the process of innovation is transitive, and each technology replaces the previous one. Such consumers never need

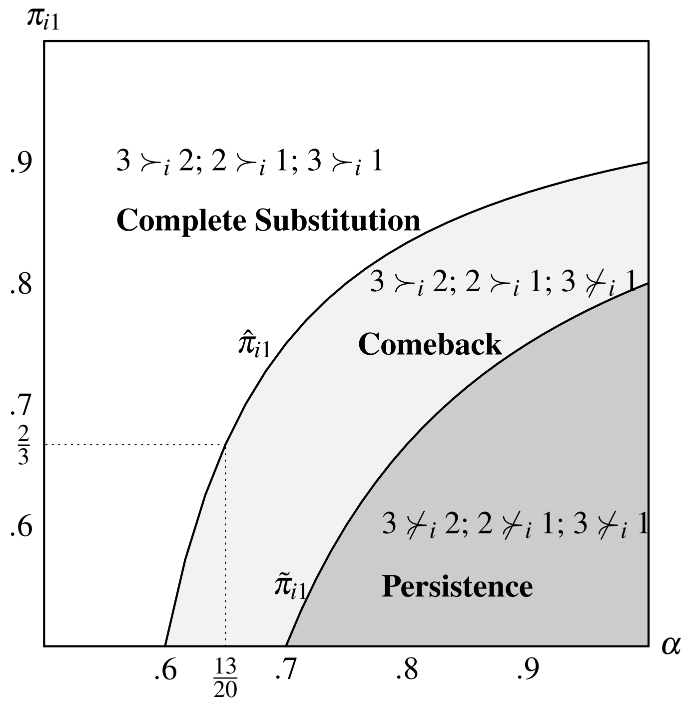

Figure 2: the process of technological substitution, with $p = \frac{1}{5}$.

more than one technology. The second area $\pi_{i1} \in (\tilde{\pi}_{i1}, \hat{\pi}_{i1})$ in light grey, situated between the two curves, corresponds to the case of technological comebacks. While the technology of the second generation completely replaces the first one, there is room for a comeback of this technology when the third generation appears. Finally, the third area $\pi_{i1} < \tilde{\pi}_{i1}$, in dark grey at the bottom right of the graph, corresponds to the case in which the two attributes are highly complementary. In this case, the two states of the world are almost equally likely to happen (low π_{i1}) and/or the product attribute that matters mostly in each state of the world is fairly distinct (high α). In this area, the first-generation technology never disappears. It becomes a complement to the second one, so that $\Lambda^* = \{1,2\}$ when $L = \{1,2\}$, and remains a complement to the third one when $L = \{1,2,3\}$, while the second-generation technology disappears: $\Lambda^* = \{1,3\}$.

Take some specific parameters as an example here. Let $\alpha = \frac{13}{20}$ and assume that probability π_{i1} for a consumer i to be in state 1 is identically distributed over $[\frac{1}{2}, 1]$ among the population of consumers. Figure 2 shows how the optimal consumption bundle varies with consumer preferences and the available technology set. On the horizontal axis is the type of a consumer, fully characterized by her frequency to be in state 1, π_{i1}. On the vertical axis are the available technology sets.

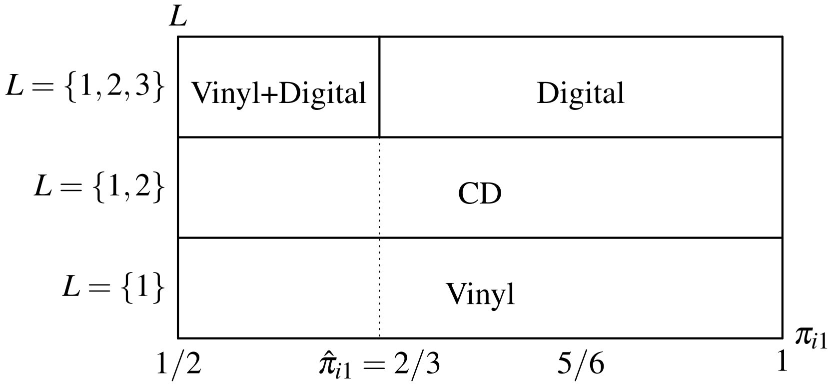

Figure 3: Consumers' optimal consumption bundles for different sets of available technologies, with $\alpha = \frac{13}{20}$, $p = \frac{1}{5}$.

In our example, no consumer keeps using vinyl all the time as long as a new generation technology ever appears ($\tilde{\pi}_{i1} < \frac{1}{2}$). Nevertheless, vinyl makes a comeback for part of the population. With the given distribution of π_{is}'s, our model predicts that, when all the three generations appear successively, one can expect a third of the consumers to choose consuming both vinyl and digital, while the rest will use digital only, with $\hat{\pi}_{i1} = \frac{2}{3}$. The former corresponds to those who are more likely to be in state 2 where attribute "object" is valued more than attribute "usability". When only vinyl is available, there is no choice and everyone uses vinyl. When CD appears, it completely substitutes vinyl. However, with the arrival of digital music, all the consumers who care sufficiently about attribute "object" (i.e. π_{i1} is sufficiently low) buy both vinyl and digital. In particular, it is only in the presence of digital music that a comeback of the vinyl is possible.

5 General results

5.1 Preliminary observations

In this subsection, we return to the general setup presented in Section 3 to present the different ways a technology can substitute another.

As in the example in Section 4, the most obvious comparison to be made between technologies is via their respective expected utilities $EU_i(v_l)$. Trivially, according to equation (1), if a unique technology is bought, it is the one that offers the highest expected utility.

We say that technology 2 *dominates in expected utility* technology 1 for consumer i if the former brings her a higher expected utility than the latter, i.e. $EU_i(v_2) = \sum_{s \in S} \pi_{is} u_s(v_2) \geq EU_i(v_1) = \sum_{s \in S} \pi_{is} u_s(v_1)$.

Lemma 1. *The relationship of dominance in expected utility is transitive, i.e. if* $EU_i(v_2) > EU_i(v_1)$ *and* $EU_i(v_3) > EU_i(v_2)$*, then* $EU_i(v_3) > EU_i(v_1)$*.*

The proof is trivial and is hence omitted. This is a standard result from utility theory, since $EU(v_j)$ is a scalar. It implies that, in our specification, a technological comeback cannot be explained by non-transitive preferences in which consumers would buy technology 2 only when 1 and 2 are available but technology 1 only when 1, 2 and 3 are available. Hence, for a comeback to be possible, it has to rely on buying, at least at some point, more than one technology.

To guarantee that a technology becomes permanently obsolete, regardless of the other available technologies, a concept stronger than dominance in expected utility, called *First-Order Stochastic Dominance (FOSD)*, is needed. We say that technology 2 first-order stochastically dominates technology 1 (2 FOSDs 1) if, for all state $s \in S$, $u_s(v_2) \geq u_s(v_1)$ and, for at least one state $s \in S$, $u_s(v_2) > u_s(v_1)$.

Lemma 2. *If technology* 2 *FOSDs technology* 1*, then technology* 1 *is never used when technology* 2 *is available.*

Indeed, it is enough to see that, according to (1), if technology 2 FOSDs technology 1, then there is no state of the world in which technology 1 has any strictly positive added-utility over technology 2. Hence, regardless of the presence of additional technologies, if any of the two is chosen, it must be 2. Like dominance in expected utility, FOSD is a transitive relationship.

We represent this relationship in the special case where there are three technologies and two states of the world in Figure 4. The vertical axis represents the value of each technology in a given state of the world. The two segments on the horizontal axis represent the two states of the world, with the length of each segment being the probability for i to be in the corresponding state. Note that the area below the curve represents for each technology its expected utility for i. In both examples, $EU_i(3) > EU_i(2) > EU_i(1)$. However, in the example presented by the left-hand-side graph in Figure 4, 3 FOSDs 2 FOSDs

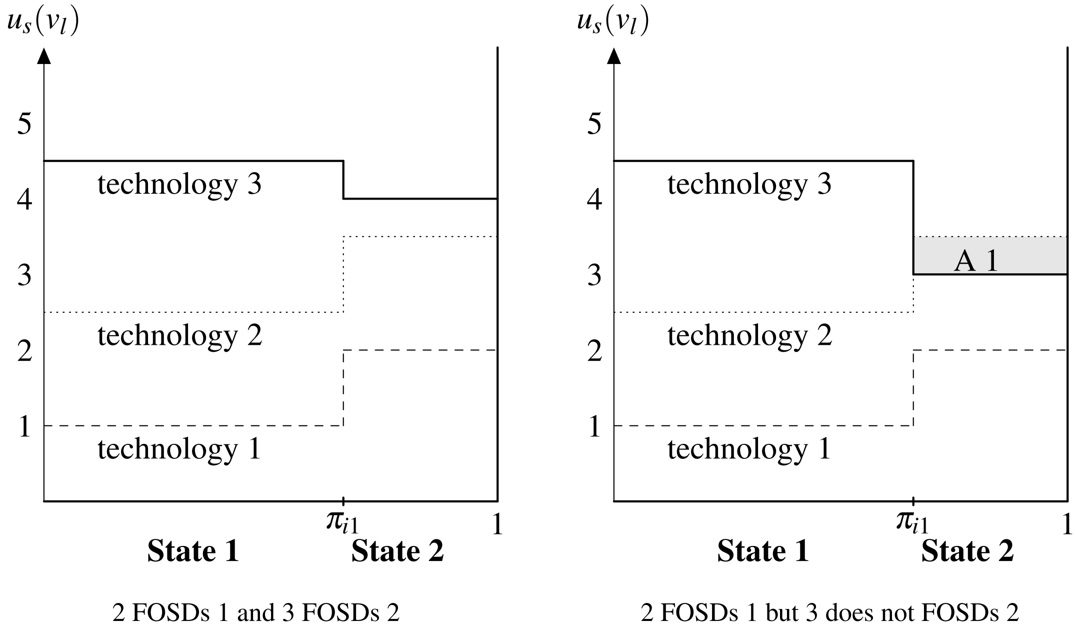

Figure 4: First order stochastic dominance.

1. On the contrary, in the example presented by the right-hand-side graph, technology 2 is better than technology 3 in some state of the world (state 2).

Definition 1. *For consumer i, technology l* ***completely substitutes*** *technology k, denoted by $l \succ_i k$, if the following is true: If k and l are the only two technologies available, then k is not in i's optimal bundle.*

It is clear by Lemma 2 that if technology l FOSDs technology k, then l completely substitutes k. But l can completely substitues k without FOSDing it, as the following lemma suggests.

Lemma 3. *If there are only two technologies,* 1 *and* 2*, available, then technology* 2 *completely substitutes technology* 1 *for consumer i if $EU_i(v_2) > EU_i(v_1)$ and*

$$\sum_{s\in S} \pi_{is} \max_{l=1,2} u_s(v_l) - \sum_{s\in S} \pi_{is} u_s(v_2) < p. \tag{2}$$

This follows again directly from the maximization problem (1). Assume that $EU_i(v_2) > EU_i(v_1)$. We already know that if consumer i buys one technology only, it is technology 2 because of its higher expected utility for her. The utility added by owning an additional technology 1 is strictly positive in the states where this older technology is more desirable than the newer one. This additional benefit corresponds to the left hand side of equation (2).

In the example presented on the right hand side of Figure 4, suppose that only technologies 2 and 3 are available, then they can coexist in the optimal bundle of the consumer (i.e. $3 \not\succ_i 2$) if and only if the grey area is larger than the cost of having an additional technology, i.e. $A1 \geq p$.

5.2 Technological comebacks

In this subsection, we study more precisely the condition of existence of a technological comeback. We define a comeback as follows.

Definition 2. *Consider three technologies of subsequent generations such that $EU_i(v_3) > EU_i(v_2) > EU_i(v_1)$. Technology 1 makes a* ***comeback*** *for consumer i if:*

(i) technology 2 completely substitutes technology 1, i.e. $2 \succ_i 1$, so that $\Lambda^* = \{2\}$ when $L = \{1,2\}$,

(ii) technology 1 is part of the optimal consumption bundle of consumer i when the third-generation technology becomes available, i.e. $1 \in \Lambda^*$ when $L = \{1,2,3\}$.

This definition implies that for a second-generation technology to make the first one temporarily disappear until the third generation makes a comeback to be possible, the process of technological substitution ($\succ_i$) must not be transitive.

Proposition 1. *The substitution relationship $\succ_i$ defined in Definition 1 is not transitive, i.e. it is possible that $3 \succ_i 2$, $2 \succ_i 1$, but $3 \not\succ_i 1$.*

The formal proof is in Appendix. Here let us just point out that a consumer, while maximizing her expected utility (cf. (1)), does not count the utility of a certain technology l in a certain state of the world s unless l is the best choice in s. If a unique technology is available to consumer i all the states, then its performance in each state matters. Whenever there are more than one technology, what matters to the consumer is the utility added by having an additional technology in each state.

The graph on the left hand side of Figure 5 illustrates an example with $2 \succ_i 1$, $3 \succ_i 2$ but $3 \not\succ_i 1$. Each new technology is better than the previous one for consumer i in expected

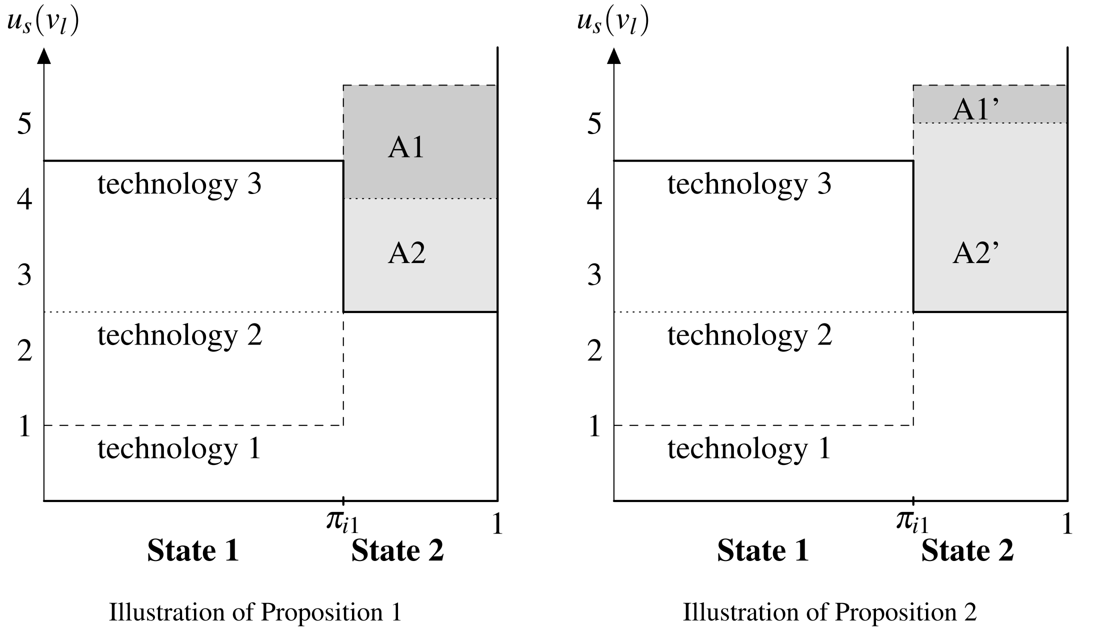

Figure 5: The substitution process is not transitive

utility: $EU_i(v_3) > EU_i(v_2) > EU_i(v_1)$. However, in the least frequent state of the world, state 2, each new technology yields a lower utility than the previous one. In this example, the area $A1$ is the loss due to the absence of technology 1 as a complement to technology 2. The area $A2$ is the loss due to the absence of technology 2 as a complement to technology 3. Hence, if $A1 < p$ and $A2 < p$, then $3 \succ_i 2$ and $2 \succ_i 1$, i.e. each technology completely substitutes the previous one. However, if $A1 + A2 > p$, technology 1 becomes a good complement to technology 3, and consumer i prefers buying both technologies 1 and 3 to having 3 only. To sum up, if only technologies 1 and 2 are available, technology 1 is obsolete. But the entry of technology 3 makes technology 2 obsolete in turn, which leaves room for technology 1 to come back.

For this result, it does not matter how better the second-generation technology performs than the first-generation one in the most likely state of the world. What is important is how it performs in the least likely one. If the second generation performs worse than the first one while the third generation performs worse than the second one in this state of the world, there is room for a possible comeback.

Proposition 2. *If technology* 1 *makes a comeback in the sense of Definition 2, then the optimal bundle when all three technologies are available is* $\Lambda^* = \{1,3\}$ *and technology* 2 *disappears. In particular, it is possible that technology 3 does not completely substitutes* *technology 2 (denoted by* $3 \not\succ_i 2$*),* $\Lambda^* = \{2,3\}$ *when* $L = \{2,3\}$*, but the comeback of technology 1 makes technology 2 disappear:* $\Lambda^* = \{1,3\}$ *when* $L = \{1,2,3\}$.

The formal proof is in Appendix. The first result of the proposition comes from the fact that, if technology 1 does not add enough value to technology 2 compared with its cost p, it certainly adds even less value to the combination of technologies 2 and 3. Hence, the only possibility for a comeback of technology 1 is that the second-generation technology becomes obsolete.

The graph on the right hand side of Figure 5 illustrate the second result of Proposition 2. Suppose that $A1' < p < A2'$ and $A1' + A2' > p$. The difference with the example on its left is that the second-generation technology is almost as good as the first-generation one in state 2. Hence, $3 \not\succ_i 2$, in contrast to the example illustrated on its left where $3 \succ_i 2$. As a result, if technologies 2 and 3 were the only available ones here, consumer i would buy both. Therefore, it is the presence of technology 1 that makes technology 2 irrelevant to the consumer. In both examples in Figure 5, if 1 and 2 are the only available technologies, the second-generation technology completely substitutes the first-generation one (i.e. condition $2 \succ_i 1$ is fulfilled). In both examples, the optimal bundle when all three technologies are available is the same — technology 2 disappears and technology 1 comes back.

In this example, the only thing that matters is whether technology 1 is better than technology 2 in state 2 ($u_2(v_1) > u_2(v_2)$), and whether the difference between the utility of technologies 1 and 3 in state 2 is sufficiently high to justify buying both ($\pi_{i2}(u_2(v_1) - u_2(v_3)) = A1' + A2' \geq p$). Since the second-generation technology is worse than the first in the less likely state of the world, the two technologies in the optimal bundle are $\Lambda^* = \{1,3\}$ when all the three generations are available. The relationship $3 \not\succ_i 2$ does not matter to the optimal bundle in the presence of three technologies.

6 Product design

In the general model, we focus on the case in which consumer heterogeneity is characterized by their different frequencies of being in each state of the world, and we do not discuss the role of heterogeneity in the valuation of each dimension. However, the latter is important in the analysis of how being in a comeback situation should influence product design. Should the rejuvenated technology be designed or advertised as mainstream or as niche, in the sense of Johnson and Myatt (2006)? To see this, consider the following variant of our model with two states of the world ($S = \{1,2\}$). Assume that technology 1 on its "advantageous" state of the world, state 2, is valued $u_{i2}(v_1) = x + \varepsilon_i$ by consumer i, where ε is a zero-mean random variable specifying the taste of each consumer. All the other contingent utilities of technologies ($u_s(v_l)$ for $s \neq 2$ or $l \neq 1$) are still common to all consumers. A product has a niche design if the dispersion (the variance of ε, for a given distribution) of consumer tastes is high. In other words, the product is designed and advertised in order to please a limited number of consumers only, with high intensity. Similarly, the product has a mainstream design if the dispersion is low. As a example, assume that ε is uniformly distributed over the interval $[-\delta, \delta]$, where $\delta \in [B, N]$ is the chosen design. Here B stands for the broadest possible mainstream design (small variance), and N for the most specialized "niche" design (high variance). A more general definition of demand rotation follows a similar intuition and would merely be a rewriting of Johnson and Myatt (2006) assuming exogenous prices.

Reformulating the main condition for a comeback (cf. equation (8) in Appendix) implies that consumer i buys technology 1 in complement to technology 3 if and only if

$$x + \varepsilon_i - u_2(v_3) = u_{i2}(v_1) - u_2(v_3) > \frac{p}{1 - \pi_{i1}} = \frac{p}{\pi_{i2}}. \tag{3}$$

Following Proposition 1 in Johnson and Myatt (2006), one can show that a marketer always chooses an extreme product design among a collection of (mean-fixed) spreads of random variable ε, i.e. either its minimum or maximum possible variance. If $x - u_2(v_3) \geq \frac{p}{\pi_{i2}}$, the probability of selling technology 1 to consumer i is maximized if the variance of ε is low. This probability becomes 1 if $u_2(v_1)$ is deterministic, i.e. $\delta = 0$ hence $\varepsilon \equiv 0$. If $x - u_2(v_3) < \frac{p}{\pi_{i2}}$, the probability of making a sale is maximized if δ is high, with the probability being 0 if $\delta = 0$ hence $\varepsilon \equiv 0$.

Denote by $\tilde{\varepsilon}_i = \frac{p}{\pi_{i2}} - x + u_2(v_3)$, the level of ε_i above which consumer i, who is in state 2 with probability π_{i2}, is willing to buy technology 1. With a design δ, the probability of making a sale to consumer i is

$$q(\pi_{i2},\delta)=\begin{cases}1 & \text{if } \tilde{\varepsilon}_i \leq -\delta,\\ \frac{\delta-\tilde{\varepsilon}}{2\delta} & \text{if } \tilde{\varepsilon}_i \in (-\delta,\delta)\\ 0 & \text{if } \tilde{\varepsilon}_i \geq \delta\end{cases}$$

For all $\pi_{i2} < \frac{p}{x-u_2(v_3)} = \tilde{\pi}_2$, the optimal design is N; otherwise it is B. Assume again π_{i1} is uniformly distributed on $[\frac{1}{2},1]$ so that π_{i2} is uniformly distributed on $[0,\frac{1}{2}]$. If sellers are able to offer the "right" design to each consumer, the probability of making a sale of technology 1 is:

$$Q=\int_0^{\tilde{\pi}_2} q(\pi_{i2},N)\mathrm{d}\pi_{i2}+\int_{\tilde{\pi}_2}^{\frac{1}{2}} q(\pi_{i2},B)\mathrm{d}\pi_{i2}.$$

Return to the example depicted in Figure 2. In the case where $\alpha=\frac{13}{20}$, there is a demand for "broad" design of vinyl for all consumers with $\pi_{i1}\in(\frac{1}{2},\frac{2}{3})$. Those consumers like enough the "object" dimension to be willing to buy a simple vinyl, designed to please everyone without taking risks. It is also possible to create additional demand by offering a niche design that may reach a part of those buyers with $\pi_{i1} > \frac{2}{3}$. Those consumers are not spontaneously willing to buy vinyl if it is designed as mainstream, but some might be attracted by a more "risky" version. Moreover, in the case where $\alpha < .6$ (the area on the top left of Figure 3), no consumer would ever buy a broad design. However, some comeback is still possible using a niche one.

Hence, equation (3) provides a simple guidance on how to choose the design. If the consumers' likelihood of being in the 'technology-1-advantageous' state of the world is low and/or if the advantage that technology 1 has over technology 3 is low in this state, the only chance to make a comeback is to try to offer a very niche design, that will please a limited number of consumers only. Else, it is possible to design a mainstream comeback aimed at most consumers.

7 Discussion and conclusions

7.1 What are the important attributes for a comeback?

Above all, the model shows that the determinant of a comeback of a technology is not its overall performance, but its specific performance in the state of the world where it adds value to the newest technology. In the case of vinyl, Bartmanski and Woodward (2015) explain that the way a vinyl complements digital is by offering a tangible object. For this reason, in order to complement digital music (often sold as a bundle with a download code for the digital version of the music), the vinyl must be designed in a way that emphasizes this dimension in particular. According to Bartmanski and Woodward (2015), p.7, recent new and re-releases of vinyl incorporate special features which play up the attractions of buying vinyl, relative to CDs and digital downloads. Heavy vinyl pressing aims at suggesting the importance of the musical content, and increasing the longevity and collectability of one's purchase. The same holds for coloured vinyl or other special features such as cover art posters.

The success of vinyl provides a fairly clear guide on which attributes a marketer or product designer would need to develop and emphasize, with the aim of organizing a comeback or the rejuvenation of a brand.

In the photography industry, the first generation of analogue films has been almost entirely replaced by the second generation of digital cameras. The third generation is based on phones and social networks, and is not originally designed for physical printing. As more and more consumers use the third generation and abandon digital cameras – according to data by the Camera and Imaging Product Association (cipa.jp), shipments of digital cameras have decreased by more than 80% between 2010 and 2016 — the physical dimension of analogue photography seems to have become a useful complement. Film photography has started its return as a niche product, with sales growing at a 5% rate annually, and Kodak is reintroducing discontinued products such as Ektachrome.[7] A very similar story can be told about the revival of Super 8 films.[8] Some consumers who had abandoned products of the first generation start using them again as a complement to the

[7] Olivier Laurent, "This is why film photography is making a comeback," Time, January 26, 2017.

[8] James Temperton, "Kodak's super 8 revival is leading a new wave of retro nostalgia," Wired, June 17, 2017.

third one.

As for vinyl, understanding and emphasizing the dimension that matters enough for some consumers is the key for a comeback to be possible. Now that the photographic experience is mostly dematerialized and has in large parts been transferred from digital cameras to smartphones, the possibility to immediately print a physical picture could be an ideal complement to social media. It seems to be the very route taken by Polaroïd, a company that had almost completely disappeared from the market.[9] Polaroïd is now producing digital cameras combined with a printing device.[10] A slightly different business model is behind Fujifilm's Instax analog cameras, of which more than 5 millions have been sold in 2016,[11] about 4 times more than Fujifilm's sales of digital devices.[12] The idea is similar in the two cases: to combine and emphasize an (almost) disappeared feature of the analogue world with the most recent technology. As shown in our model, what determines the success of such products is whether there are states of the world in which consumers sufficiently value the features that complement the newest technology.

In the mobile phone industry, there are no strictly speaking three generations replacing each other. However, the subsequent successful innovations in the market have in common to improve the product on most dimensions, except for the solidity and the battery life. Hence, if for some consumers these dimensions matter sufficiently, there is room for a niche return of phones resembling disappeared ones. HMD – the company that took over Nokia phones from Microsoft – announced the return of the "3310" model in 2017, based on a similar idea. The company claims that there is a demand for some of the attributes of the original 3310 (low price, long battery life, simplicity) that could make it an ideal complement to smartphones.[13] The attribute of Nokia's 3310 that may carry over through time is often described as being "perhaps the most resilient and long-lasting

[9] Andrea Nagy Smith, "What was Polaroid thinking?," Yale Insights, November 9, 2009.

[10] Johanna Stern, "Smile! The Polaroid-Style Instant Camera Is Back," The Wall Street Journal, May 18, 2016 and Emmanuel Tsekleves, "The enduring appeal of analogue in a digital world," The Conversation, January 12, 2015.

[11] "Fujifilm zooms In on Instax's Retro Appeal in a Digital Age, "The Wall Street Journal," April 1st, 2016.

[12] "Fujifilm's Instax Analog Camera is outselling its digital devices by nearly 4 times," Digital Trends, April 4m 2016.

[13] See for instance James Temperton, "Nokia 3310 and Snake are back...but there's a catch," Wire, February 28, 2017.

phone ever made."[14] Hence, if the company intends to make some attributes of the product prominent (in the sense of Chakraborty and Harbaugh, 2014), it should be the ones that really differentiate the product from a smartphone and emphasize its complementarity. The company seems to have captured the idea and has been focusing a large part of their communication on the long life of the battery.[15]

7.2 How do we know if a technology is ready for a comeback?

First of all, if a technology has been replaced by another one which is better in every possible dimension, no comeback is possible. This corresponds to the FOSD result of Lemma 2. Second, it should be possible to replace the technology that has "predated" potential coming-back one by a combination of an even newer one and the coming-back one. However, as pointed out by Proposition 2, the second-generation technology does not need to have disappeared to make the comeback possible. For instance, in the absence of vinyl, some consumers attracted by the "object" attribute can well be ready to buy CD instead. Thus, the marketers should not wait for the complete disappearance of the second generation. Instead, they need to evaluate whether it is possible to make the second generation disappear by combining the coming-back technology with the newest one. This is also one of the lessons from the success of current releases of new vinyl: They are marketed in combination with digital technology so that consumers understand immediately the complementarity.

The market for toys is experimenting similar attempts of bundling by the industry. A three-generation representation of this market would be that the sales of a first generation of traditional physical toys – such as Lego building blocks – have been declining with the apparition of a second generation of more sophisticated toys and electronic games.[16] Now that a third generation of dematerialized entertainment is largely available for children, it becomes possible to organize partial comebacks of a rejuvenated version of the first

[14] Andrew Griffin, "Nokia 3310, 'the most reliable phone ever made', to be re-launched at MWC 2017," The Independent, Tuesday 14 February 2017

[15] "Nokia 3310 relaunched with even longer battery life of 22 hours – 10 times the original," Irish Times, February 28, 2017.

[16] See for instance Nick Watt and Hana Karar, "The land where Lego comes to life," Abc News, November 16, 2009 and Knowledge@Wharton , , Craig McLean, "Lego, play it again," The Telegraph, December 17, 2009, "Innovation Almost Bankrupted Lego - Until It Rebuilt with a Better Blueprint," Time, July 23, 2012.

generation using complementarities, “from cartoon to video games to films to physical toys”.[17] In particular, Lego blocks thrive as a complement to social media, with fan videos shared on Youtube (and its application for children) often being described as one of the reasons sales of construction toys have surged.[18] Such a complementarity is a deliberate choice of the companies, not a sudden wave of nostalgia for older products. While the contemporary building blocks are not so technologically different from what they were 20 years ago, the storytelling that accompanies them is making a large use of the most recent technologies.

7.3 Conclusion

This research contributes to the literature on innovation and product substitution, as well as the one on product positioning and design. Our model is based on utility-maximizing consumers in a static context. We provide a simple and testable condition on consumer choice for a technological comeback to be possible with time-independent preferences. A first limitation of our approach is that we do not disentangle our “fundamental” notion of comeback (complementarity) from possible changes in preferences. Nevertheless, in our model if complementarities exist, nostalgia (and the changes in preferences representing it) could only increase the demand for a comeback.

A first immediate extension to the model would be to dig further into the consumer choice in a multi-attributes context. A second one would be to explicitly develop the dynamic of comebacks in models of technological substitutions. A third one could be to develop further the strategic role of the marketer, beyond the simple model of product design we develop in Section 6.

[17] Child’s play, “The Economist”, September 9th 2013

[18] Gregory Schmidt, “Lego’s success leads to competitors and spinoffs, “The New York Times,” November 20, 2015.

Appendix

Proofs

Proof of Proposition 1. Consider a case with 2 states of the world ($S = \{1,2\}$) and start with the first and the second generations available only ($L = \{1,2\}$). Assume (1) $EU_i(v_2) > EU_i(v_1)$ for consumer i, (2) state 1 happens more often for consumer i ($\pi_{i1} > \frac{1}{2}$), and (3) the second-generation product is strictly better in state 1 ($u_1(v_2) > u_1(v_1)$). Consumer i uses technology 2 exclusively if (i) $\{2\}$ is averagely better than $\{1\}$, which is true because $EU_i(v_2) > EU_i(v_1)$; and (ii) $\{2\}$ is better than $\{1,2\}$, which means that $\pi_{i1}u_1(v_2) + \pi_{i2}u_2(v_2) - p > \pi_{i1}u_1(v_2) + \pi_{i2}\max_l u_2(v_l) - 2p$ (recall that $u_1(v_2) > u_1(v_1)$) or, equivalently, $\pi_{i2}u_2(v_2) + p > \pi_{i2}\max_l u_2(v_l)$. This condition is satisfied if

$$\text{either } u_2(v_2) \geq u_2(v_1); \tag{4}$$

$$\text{or } u_2(v_2) < u_2(v_1),\ \pi_{i1} > 1 - \frac{p}{u_2(v_1) - u_2(v_2)}. \tag{5}$$

In the example in Section 4, (5) simplifies to $\pi_{i1} > 1 - \frac{p}{2\alpha - 1} = \tilde{\pi}_{i1}$. These conditions represent $2 \succ_i 1$ and specify the idea that either the second-generation technology is better in both dimensions, i.e. 2 FOSDs 1 (condition (4)), or it is inferior in state 2, but the loss of using it in this state is compensated by p, the spared cost of having technology 1 in addition to technology 2 (condition (5)).

Similarly, if only second and third generations are available ($L = \{2,3\}$), since $EU_i(v_3) > EU_i(v_2)$ and $u_1(v_3) > u_1(v_2)$, consumer i uses technology 3 ($3 \succ_i 2$) exclusively if

$$\text{either } u_2(v_3) \geq u_2(v_2); \tag{6}$$

$$\text{or } u_2(v_3) < u_2(v_2),\ \pi_{i1} > 1 - \frac{p}{u_2(v_2) - u_2(v_3)}. \tag{7}$$

Now suppose that conditions (5) and (7) are fulfilled for consumer i. Explicitly, $u_1(v_3) > u_1(v_2) > u_1(v_1)$, $u_2(v_3) < u_2(v_2) < u_2(v_1)$ and $\pi_{i1} > 1 - \frac{p}{\max\{u_2(v_1) - u_2(v_2), u_2(v_2) - u_2(v_3)\}}$. Hence a technology of a generation g always completely substitutes the one of the previous generation $g-1$, but is strictly inferior to $g-1$ in the less likely state, state 2.

Consumer i can still choose the first-generation technology when the second and the third generations are available, i.e. $\{1,3\}$ is the optimal bundle in $\{1,2,3\}$. It is easy to see that $\{1,3\}$ is better than $\{1,2\}$, $\{2,3\}$ and $\{1,2,3\}$. By (5) and (7) we rule out that $\{1\}$ and $\{2\}$ are the optimal bundle, because $\{1\}$ is strictly dominated by $\{2\}$, and $\{2\}$ by $\{3\}$.

It is thus enough to show that $\{1,3\}$ is preferred to $\{3\}$ so as to have $3 \not\succ_i 1$,

$$\pi_{i1} < 1 - \frac{p}{u_2(v_1) - u_2(v_3)}. \tag{8}$$

In the example in Section 4, (8) simplifies to $\pi_{i1} < 1 - \frac{p}{2(2\alpha-1)} = \hat{\pi}_{i1}$. Denote $u_1(v_3) - u_1(v_2) = a$, $u_1(v_2) - u_1(v_1) = b$, $u_2(v_1) - u_2(v_2) = c$, and $u_2(v_2) - u_2(v_3) = d$. Then $a,b,c,d > 0$ and the conditions that π_{i1} should satisfy are summarized here (recalling that $EU_i(v_3) > EU_i(v_2) > EU_i(v_1)$ and $\pi_{i1} > \frac{1}{2}$):

$$\max\left\{\frac{1}{2}, 1 - \frac{p}{\max\{c,d\}}, \frac{d}{a+d}, \frac{c}{b+c}, \right\} < \pi_{i1} < 1 - \frac{p}{c+d}, \tag{9}$$

This is possible only if

$$p < \min\left\{\frac{1}{2}, \frac{b}{b+c}, \frac{a}{a+d}\right\} \cdot (c+d). \tag{10}$$

The fact that $2 \succ_i 1$, $3 \succ_i 2$ and $3 \not\succ_i 1$ implies the non transitivity of the substitution relationship. Given our assumptions, substitutions are not transitive for consumer i for *some* value of $\pi_{i1} \in (\frac{1}{2}, 1)$ if and only if the technology cost p satisfies (10).

Finally, note that a comeback of technology 1 happens however for each consumer i for which $\pi_{i1} > \frac{1}{2}$ and conditions (5) (the first technology disappears) and (8) (the comeback) are met, regardless of whether $3 \succ_i 2$ is fulfilled. □

Proof of Proposition 2. We are considering a comeback situation in the sense of Definition 2. Hence we have to show that (i) technology 1 is part of the optimal bundle in $\{1,2,3\}$ and (ii) technology 1 is not part of the optimal bundle in $\{1,2\}$. First, we know that $\{1\}$ is not the optimal bundle, because $EU_i(v_2) > EU_i(v_1)$ is a necessary condition for (ii) (or by Definition 2). Secondly, $\{1,2\}$ cannot be the optimal bundle, because 2 completely substitutes 1 by Definition 2. We are left with two possible optimal bundles, $\{1,3\}$ and $\{1,2,3\}$. Let us show by contradiction that $\{1,2,3\}$ cannot be the optimal bundle.

Assume that $\Lambda^* = \{1,2,3\}$ when $L = \{1,2,3\}$. Recall that $\Lambda^* = \{2\}$ when $L = \{1,2\}$. Therefore, by definition of an optimal bundle,

$$\sum_{s\in S} \pi_{is} \max_{l=1,2,3} u_s(v_l) - \sum_{s\in S} \pi_{is} \max_{l=2,3} u_s(v_l) > p,$$
$$\sum_{s\in S} \pi_{is} \max_{l=1,2} u_s(v_l) - \sum_{s\in S} \pi_{is} u_s(v_2) < p.$$

Equivalently, $\sum_{s\in S} \pi_{is}[u_s(v_1) - u_s(v_2)]^+ < p < \sum_{s\in S} \pi_{is}[u_s(v_1) - \max_{l=2,3} u_s(v_l)]^+$, where $[x]^+ = \max\{x, 0\}$. This implies that

$$\sum_{s\in S} \pi_{is} \Big\{ \big[u_s(v_1) - u_s(v_2)\big]^+ - \big[u_s(v_1) - \max_{l=2,3} u_s(v_l)\big]^+ \Big\} < 0 \qquad (11)$$

However, for all $s \in S$, $u_s(v_2) \leq \max_{l=2,3} u_s(v_l)$ which implies that $u_s(v_1) - u_s(v_2) \geq u_s(v_1) - \max_{l=2,3} u_s(v_l)$ and, consequently, $\big[u_s(v_1) - u_s(v_2)\big]^+ \geq \big[u_s(v_1) - \max_{l=2,3} u_s(v_l)\big]^+$. Therefore (11) is impossible. Indeed, (11) means that the value of technology 1 to a bundle containing both technologies 2 and 3 is higher than to a bundle containing technology 2 only.

Next let us give an example where $\{1,3\}$ is the optimal bundle in $\{1,2,3\}$ and $\{2,3\}$ is the optimal bundle in $\{2,3\}$.

Assume that $S = 1,2$, $u_1(v_3) > u_1(v_2) > u_1(v_1)$, $u_2(v_1) > u_2(v_2) > u_2(v_3)$, $EU(v_3) > EU(v_2) > EU(v_1)$, and technology 2 completely substitutes 1, i.e. $\{2\}$ is the optimal bundle in $\{1,2\}$. Denote $u_1(v_3) - u_1(v_2) = a$, $u_1(v_2) - u_1(v_1) = b$, $u_2(v_1) - u_2(v_2) = c$, and $u_2(v_2) - u_2(v_3) = d$.

First, for $\{1,3\}$ to be the optimal bundle in $\{1,2,3\}$, one must have (i) $\{1,3\}$ is better than $\{3\}$: $\sum_{s\in S} \pi_{is} \max_{l=1,3} u_s(v_l) - \sum_{s\in S} \pi_{is} u_s(v_3) > p$ which means that $\pi_{i2} > \frac{p}{c+d}$, and (ii) $\{1,3\}$ is better than $\{2,3\}$ (1 being preferred to 2 as a complement to 3): $\sum_{s\in S} \pi_{is} \max_{l=1,3} u_s(v_l) - \sum_{s\in S} \pi_{is} \max_{l=2,3} u_s(v_l) > 0$ which is satisfied by assumption.

Next, $EU_i(v_3) > EU_i(v_2) > EU_i(v_1)$ requires that $\pi_{i2} < \frac{a}{a+d}$ and $\pi_{i2} < \frac{b}{b+c}$. Finally, technology 2 substituting technology 1 requires, in addition, $\sum_{s\in S} \pi_{is} \max_{l=1,2} u_s(v_l) - \sum_{s\in S} \pi_{is} u_s(v_2) < p$ or, equivalently, $\pi_{i2} < \frac{p}{c}$.

To summarize, one has only to have $\frac{p}{c+d} < \pi_{i2} < \max\{\frac{p}{c}, \frac{b}{b+c}, \frac{a}{a+d}\}$. Besides, for this to be possible, we impose that $\frac{p}{c+d} < \min\{\frac{b}{b+c}, \frac{a}{a+d}\}$ or, equivalently, $(b-p)c + (d-p)b > 0$ and $(c-p)a + (a-p)d > 0$, which is true when a, b, c, d are all greater than p, for example. □

Heterogeneous prices

Consider a variant of the main model, but assume that instead of a single price p, there exists a price $p_l \geq 0$ for each available technology l in the set L. Equation (1) that determines the expected utility of a bundle Λ_i for a consumer i rewrites

$$f_i(\Lambda_i) = \sum_{s \in S} \pi_{is} \max_{l \in \Lambda_i} u_s(v_l) - \sum_{l \in \Lambda_i} p_l, \tag{12}$$

with the optimal bundle still solving $\Lambda_i^* = \arg\max_{\Lambda_i \subset L} f_i(\Lambda_i)$. As Propositions 1 and 2 are claims of existence, their proof holds when allowing for heterogeneous prices. The only way in which different prices affect the model, is that what determines whether a technology is preferred to another is the relative prices of technologies, while what determines whether a technology adds enough value to a given bundle is its absolute price. More precisely, Lemma 3 rewrites as:

Lemma 4. *If there are only two technologies,* 1 *and* 2*, available, then technology* 2 *completely substitutes technology* 1 *for consumer i if* $EU_i(v_2) - p_2 > EU_i(v_1) - p_1$ *and*

$$\sum_{s \in S} \pi_{is} \max_{l=1,2} u_s(v_l) - \sum_{s \in S} \pi_{is} u_s(v_2) < p_1. \tag{13}$$

Hence, for technology 2 to be preferred to technology 1, its "value-for-money" (the value net of the price) must be higher. However, once we know that technology 2 is part of the bundle, what matters to whether technology 1 is a good complement is how much value it brings on top of technology 2 only, compared to the price p_1. The price of technology 2 is not relevant to this question.

For instance, in the example discussed in Section 4, the condition for each technology to be better than the previous one for consumer i is $EU_i(v_3) - p_3 > EU_i(v_2) - p_2 > EU_i(v_1) - p_1$. However, consumer i stops buying technology 1 when technology 2 becomes available if

$$\pi_{i1} > 1 - \frac{p_1}{2\alpha - 1} = \tilde{\pi}_{i1}, \tag{14}$$

ans she stops buying technology 2 when technology 3 becomes available if

$$\pi_{i1} > 1 - \frac{p_2}{2\alpha - 1}. \tag{15}$$

There is a comeback of technology 1 if both conditions (14) and (15) are satisfied and

$$\pi_{i1} < 1 - \frac{p_1}{2(2\alpha - 1)} = \hat{\pi}_{i1} > \tilde{\pi}_{i1}. \tag{16}$$

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