GROWTH MODELS FOR MULTI-PRODUCT INTERACTIONS:
Current Status and New Directions

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ABSTRACT

In this chapter, we explore the issues associated with the market dynamics of multiple, interacting product categories. First, the literature related to the multi-product growth models is reviewed. Next, we propose an expanded conceptual framework that identifies a more complete range of possible interactions among multiple products. We then offer a more general model structure based on the aggregate-level dynamic models used by ecologists, sociologists, and technology researchers to study interactions among several competing population species. Finally, we outline some promising areas for future research.
INTRODUCTION

From a marketing strategy perspective, the importance of understanding the market dynamics of multiple, interacting product categories\(^1\) has been extensively discussed (e.g., Kerin, Mahajan, and Varadarajan 1990; Czepiel 1992). Multi-product\(^2\) interactions are often viewed in the context of competition between a new entrant and the mature products it replaces. Consequently, competitive behaviors reflect the strategies and responses associated with such incursions. In this concept of the competitive market, multiple products compete with each other by offering better “performance per dollar” to potential buyers (e.g., Day 1986). The literature has termed one type of interaction as *technological substitution* between successive generations, usually of a single product category, wherein the newer product generation eventually displaces the older and the older generation either has little effect upon, or actually contributes to, the success of the newer (e.g., Foster 1986). Such inter-product relationships can affect the sales of any given product, and may help explain the S-shaped growth pattern of cumulative sales and the inflection points often observed (albeit retrospectively) in the life cycle pattern of that new product.

It is our contention however, that the interactions among multiple product categories are

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\(^1\)In this chapter, we do not consider the competition between firms within a product category, nor do we emphasize product diffusion across countries. Inter-firm competition is considered in the chapter by Chatterjee, Eliashberg, and Rao, and inter-country diffusion is discussed in the chapter by Dekimpe, Parker, and Sarvary.

\(^2\)Our discussion can be framed in terms of either (or all of) products, processes, or technologies. However, in discussing the marketing interactions among processes or technologies, these processes and/or technologies are really behaving as *products* --- albeit products used in the manufacture or sale of other products. They are often sold as such by the organizations that design and vend the processes and technologies. This is particularly clear in business-to-business markets. End-users do not generally purchase processes or technologies *per se*, but rather they purchase products that embody a technology or process. Different processes or technologies may even be associated with different product categories (e.g., analog and digital cellular telephones) which can eventually be recognized as separate product variants or subcategories. Consequently, in this paper we refer only to *products* --- it being understood that processes and technologies may be relevant to the issues discussed.
potentially much broader than such technological substitution arguments alone would suggest. Space does not permit an extensive discussion beyond the logic underlying our arguments; further elaboration, as well as conceptual and theoretical support, is provided by Ratneshwar, Shocker, and Srivastava (1997) and Dickson (1992). It has been oft noted that, from the buyer’s perspective, a product can be viewed as a bundle of benefits and costs. Which benefits and costs matter to a given purchaser often depends upon the particular buyer as well as the context and purpose in which, or for which, the product is to be used. We note only that different products can become substitutes because they provide similar desired benefits/costs---despite using different processes or technologies in their fabrication and marketing. The benefits desired for a specific application could also require a combination of multiple products, not all of which may be provided by the same producer (e.g., the components in a stereo music system). So, the buyers’ perception of the “product” may be different from that of the producer. In some instances, producer products may serve as components in some broader product definition (e.g., an “all-in-one” multi-function machine with printer, scanner, copier, and fax capabilities). The benefits desired may differ with application even though the nominal product remains unchanged (e.g., a coffee mug for drinking coffee versus one for a souvenir collection).

All successful new products are the purposeful creations of both producers and consumers. By their actions, producers make alternatives available; by the magnitude of their purchase and use, consumers determine the degree of product success. Producers want the economic profits usually obtained through some type of competitive advantage and may research consumer needs toward that end. They look to distinguish their product offerings from competitors. Buyers want solutions to their problems or satisfaction of their needs, which, in turn, determine the criteria by which the offerings of different producers are evaluated. Buyers
are also free to mix and match available producer offerings, and sometimes use these products for different purposes than originally intended by producers. The interaction between these supply and demand forces leads to differentiation and innovation. Economics, technology, logistics (availability) and knowledge/expertise are factors that constrain the process. In trying to adapt to competitors, firms can make mistakes because they misjudge or otherwise fail to understand (e.g., Dickson 1992). The market success of a given product generation may even be aided (rather than abetted) by what is happening with another product or product generation. Moreover, inter-product relationships may extend across product categories since category boundaries are often defined for the convenience of industry participants (be they consumers or producers) rather than being based solely upon consumer perceptions of solutions to their problems (e.g., although physically resembling other wines, varietal wines may have different uses and different competitive categories, such as premium beers or liquors or even bottled waters).

Thus, the general topic of multi-product interactions is both interesting and important. It is interesting because the underlying dynamics between products is associated with some rich and complex firm and consumer behavior. It is important because understanding the inter-product relationships should lead to better product forecasting as well as a more effective allocation of marketing resources. The purpose of this paper is to discuss the current status of growth models that incorporate multi-product interactions, provide a more general taxonomy of such relationships, and to outline potential directions for future research on this topic.

[insert Figures 1 and 2 about here]

To amplify our thinking on multi-product interactions, consider the sales curves for successive generations of desktop personal computers in Figure 1 and the average
(real) price patterns in Figure 2. In these figures, product generations are defined based on CPU technology (8-bit technology includes Intel’s 8080 and Zilog’s Z80, 16-bit technology includes Intel’s 8086 and 80286, 32-bit technology includes Intel’s 80386 and 80486; see Bayus 1998 for the details of these data). Even in this industry where it is acknowledged that technology is rapidly improving, it is difficult to actually observe the complete substitution of one product technology for another since the product life cycles are relatively long.

These figures clearly indicate that multiple products remain available at any point in time, with sales of each responding quite differently to price. These products have different sales growth and decay rates, as well as different peak sales levels. Such inter-product relationships can exist across the various product-market levels (i.e., industry, product category, product form, product technology, product model, or brand model; see Bayus 1998). Accordingly, we suggest that any conceptual, empirical, or normative model that seeks to explain the dynamics associated with multi-product interactions must be flexible enough to generate a wide range of sales patterns. At the same time, it is clear that the cumulative sales for each product has the familiar S-shaped growth pattern.

Consumer and producer behavior in this industry is also relatively complex (e.g., even though a next-generation product technology was available, 46 percent of new firms introduced a personal computer with older technology; Bayus 1998).

The remainder of this paper is organized as follows. We first review the literature related to multi-product growth models. Next, we propose an extended conceptual framework for considering the range of possible product interactions. We then offer a general model structure, and outline some promising areas for future research.
A REVIEW OF THE LITERATURE

Even though the importance of analyzing multi-product relationships within the broader perspective of a competitive market has long been recognized (e.g., Kerin, Mahajan, and Varadarajan 1990; Czepiel 1992; Farrell 1993a), growth models for multi-product interactions have received relatively little empirical or normative attention in the marketing literature. In general, the existing research on this topic can be divided into two main streams: (1) research that extends single-product diffusion models to account for possible multi-product interactions, and (2) models that concentrate on the diffusion of successive product generations. We first review these two research streams and then discuss some more recent research incorporating marketing decision variables into these models.

Extensions of the Single-Product Diffusion Model

Probably the earliest marketing paper to consider the diffusion of multiple products is Peterson and Mahajan (1978). Building on the original Bass (1969) single-product diffusion model, they propose a system of diffusion equations for different types of inter-product relationships. Letting \( F_i(t) \) be the cumulative proportion of adopters of product \( i \) up to time \( t \), their basic model for two products is:

\[
\frac{dF_i}{dt} = \left( a_i + b_i F_i(t) + c_i F_j(t) \right) \left[ N_i - F_i(t) \right] \quad i, j = 1, 2; \quad i \neq j
\]

Here, \( \frac{dF_i}{dt} \) represents the fraction of the population adopting product \( i \) at time \( t \) and \( N_i \) is the ceiling on the proportion of adopters for product \( i \). The \( a_i, b_i \) coefficients are similar to those of

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3 In this section, we limit our discussion to multi-product growth models. See Kim (1998) for a review of inter-category effects on the product category choice decision. Russell, Ratneshwar and Shocker (1999) offer an extensive discussion of inter-category effects on choice decisions. Inter-category effects on diffusion depend upon there being inter-category effects in buyer decision-making.
the Bass (1969) model (i.e., the coefficients of external and internal influence). The $c_i$ coefficients, however, are unique to this model and are meant to capture any inter-product interactions. Peterson and Mahajan (1978) identify various multi-product interactions according to the sign of these $c_i$ coefficients. If both $c_1$ and $c_2$ are positive, then the two products are termed “complementary.” If both coefficients are negative, then the products are considered “substitutes.” And, if one coefficient is positive and the other is zero, then one product enhances the adoption of the other and this situation is termed to be one of “independence.”

The model in (1) has received some limited empirical attention. Peterson and Mahajan (1978) use this model to empirically estimate the substitution relationship between black & white and color television, and the independent situation among insurance policies. Bucklin and Sengupta (1993) use the complementary products formulation of (1) to empirically study the co-diffusion of supermarket scanners and the use of UPC symbols. Mahajan and Muller (1994) empirically study the case of complementary products in the diffusion of videocassette recorders across the countries comprising the European Community. Eliashberg and Helsen (1994) use the independent products formulation of (1) to empirically study the lead/lag behavior of VCR diffusion between eight European countries, and Putsis, et.al. (1997) address this same issue by studying a more general formulation involving different possible mixing behaviors between the product adopters.

Peterson and Mahajan (1978) also suggest a formulation for the situation of “contingent products,” i.e., the potential market for one product is dependent upon the cumulative number of adopters of the other product. For example, if Product 2 is contingent on Product 1 the system of diffusion equations is:
Related to this general idea, Bayus (1987) considers the diffusion of a hardware product and its associated software. In his model, software sales at time $t$ are a function of hardware sales in previous time periods, i.e.,

$$S(t) = \sum_j \int_0^t H_j(\tau) \rho_j(t-\tau) d\tau$$

Here, $S(t)$ is total software sales at time $t$, $H_j(\tau)$ is the hardware sales for segment $j$ at time $\tau$, and $\rho_j(\tau)$ is segment $j$’s software purchase rate $\tau$ time periods after the hardware was purchased. Heterogeneous consumer behavior is incorporated in this framework through different price sensitivities, awareness levels, and purchase intentions for several market segments. He finds that this approach provided good forecasts of compact disc player and pre-recorded disc sales.

Gupta, Jain, and Sawhney (1997) also consider the “chicken-and-egg” relationship between a new hardware product and its software in the context of the high-definition television industry by modeling consumer demand as a function of individual utilities (obtained via a conjoint task) for various combinations of hardware and software (i.e., programming). In their approach, digital television hardware sales are obtained as a share (which is a function of software availability) of total high-end television sales (which is modeled via a single-product diffusion equation).

**Models of Successive-Product Generations**

The study of technological substitution has a long and rich history in the literature. Many studies have developed and estimated two-generation technological substitution models (e.g., see Kumar and Kumar 1992). Successive product generations can be regarded as a particular case of

$$\frac{dF_1}{dt} = \left[a_1 + b_1 F_1(t)\right][N_1 - F_1(t)]$$

$$\frac{dF_2}{dt} = \left[a_2 + b_2 F_2(t)\right][F_1(t) - F_2(t)]$$
Multi-product interactions in which it is implicitly assumed that each successive product
generation dominates the previous generation (i.e., there is a one-way product interaction in that
the newest generation only has a negative impact on the previous generation’s market size).

In marketing, the pioneering work is usually credited to Norton and Bass (1987).

Letting $S_i(t)$ be cumulative sales of product generation $i$ in time period $t$, their two-generation
model is:

$$S_1(t) = m_1 F(t) - m_1 F(t) F(t - \tau_2)$$
(5)

$$S_2(t) = m_2 F(t - \tau_2) + m_1 F(t) F(t - \tau_2)$$
(6)

Here, $m_i$ is the (estimated) constant market potential of generation $i$ and $F(t)$ is the cumulative
fraction of adoptions by time $t$ for each generation. Also, $F(t - \tau_2) = 0$ for $t < \tau_2$ where $\tau_2$ is the
time period in which Generation 2 is launched. For estimation purposes, the same S-shaped
cumulative adoption function is used for both product generations:

$$F(t) = \frac{1 - e^{-(a+b)t}}{1 + \frac{b}{a} e^{-(a+b)t}}$$

where $a$, the coefficient of external influence, and $b$, the coefficient of internal influence, are
assumed to be constant across product generations.

In equation (5), the term $m_1 F(t) F(t - \tau_2)$ represents the portion of estimated sales for
the first generation product which is lost to the second generation product once it is introduced.
The second-generation product has its own (estimated) constant market potential $m_2$. In addition,
the second-generation product augments its sales with those taken from the first-generation
product. This model is structured so that a later generation product can only reduce the sales of
an earlier generation product, and, more importantly, an earlier product generation cannot detract
dynamically from the market potential of a later one (i.e., because $m_2$ is presumed constant).
Norton and Bass (1987) use this general model structure to fit historical growth patterns of semi-conductor sales, and later apply it to several other repeatedly purchased products including pharmaceuticals and disposable diapers (Norton and Bass 1992). Johnson and Bhatia (1997) report good results for wireless communication users. Islam and Meade (1997) allow the adoption function coefficients \( a, b \) to vary across successive product generations, and they obtain good empirical fits for observed technological product substitution patterns within the mainframe computer and cellular phone categories. Mahajan and Muller (1996) propose a diffusion model for the case of successive generations of durable goods which extends equation (1) with structural ideas from the system in (5) and (6), and they empirically study diffusion and substitution in the installed base of mainframe computers.

More recently, Kim, Chang, and Shocker (1998) propose a general model framework that incorporates both inter-category dynamics and inter-generational substitution effects for a multi-product market. For the case of \( K \) interactive product categories and \( N_k \) successive product generations for each category, they define the following terms:

\[ t_{kn}^* = \text{the time period that generation } n \text{ of category } k \text{ was launched} \]

\[ r_{k'n'-kn} = (\text{estimated}) \text{ impact of generation } n' \text{ of category } k' \text{ on the market potential of generation } n \text{ of category } k \ (k \neq k') \]

\[ m_{kn}(t) = (\text{estimated}) \text{ market potential for generation } n \text{ of category } k \text{ at time } t \]

\[ m_{kn0} = (\text{estimated}) \text{ constant base factor for market potential } m_{kn}(t) \]

\[ S_{kn}(t) = \text{number of units-in-use of generation } n \text{ of category } k \text{ at time } t \]

\[ F_{kn}(t-t_{kn}^*) = \text{market penetration rate by generation } n \text{ of category } k \]

Their model formulation then becomes:
\begin{equation}
S_{kn}(t) = m_{kn}(t)F_{kn}(t-t_{kn}^*) + \\
m_{k,n-1}(t)F_{k,n-1}(t-t_{k,n-1}^*)F_{kn}(t-t_{kn}^*) + \\
m_{k,n-2}(t)F_{k,n-2}(t-t_{k,n-2}^*)F_{k,n-1}(t-t_{k,n-1}^*)F_{kn}(t-t_{kn}^*) + \cdots \\
\vdots \\
\cdots + m_{k1}(t)F_{k1}(t-t_{k1}^*)F_{k2}(t-t_{k2}^*)F_{k3}(t-t_{k3}^*) \cdots \\
F_{k,n-2}(t-t_{k,n-2}^*)F_{k,n-1}(t-t_{k,n-1}^*)F_{kn}(t-t_{kn}^*)] \\
[1-F_{k,n+1}(t-t_{k,n+1}^*)]
\end{equation}

where

\begin{equation}
m_{kn}(t) = m_{kn0} \prod_{i=1}^{K} \prod_{j=1}^{N_i} (S_{ij}(t))^{r_{ij-kn}}
\end{equation}

Here, \( F_{kn}(t-t_{kn}^*) = 0 \) for \( t < t_{kn}^* \), and \( F_{kj}(t-t_{kj}^*) = 0 \) for \( j > N_k, \forall k \).

In this system of equations, only the (estimated) market potential of one generation of a given product category (not the other model parameters) is affected by the sales of the other categories (and of their technology generations, as appropriate) as shown in equation (8). The influence of other product generations in the same product category is modeled via the technological substitution process in equation (7). Inter-product interactions are captured by the \( r_{x-x} \) parameters in equation (8), and can take on various forms since these parameters can be significantly positive, negative, or zero. If they are known \textit{a priori}, substitutions among product generations can be structurally imposed upon the model by equation (7), as in Norton and Bass (1987). Alternatively, these relationships can be determined by the data. After substituting equation (8) into equation (7), Kim, Chang, and Shocker (1998) simultaneously estimate this system of equations using data from the Korean and Hong Kong wireless communication markets. Interestingly, they find instances of complementary and substitution effects as well as a
situation in which two products have opposite effects on each other (e.g., pagers have a positive effect on the diffusion of cellular phones and, at the same time, cellular phones negatively influence the diffusion of pagers).

**Models With Marketing Decision Variables**

Up to this point, our literature review has focused only on growth models that have addressed aspects of multi-product interactions. However, it is also important to understand the possible impact of strategic decision variables on sales growth when multiple products are interacting in a market. Although generally limited to the case of technological product substitution, researchers have begun to study the role of various marketing decision variables. Some work on the multi-product entry timing decision for a monopolist (e.g., Wilson and Norton 1989; Mahajan and Muller 1996; Pae 1997) and duopolist (e.g., Kalish, Mahajan, and Muller 1995; Bayus, Jain, and Rao 1997) has been conducted. Sequential distribution strategies for movies (theaters and videocassette tape) are considered by Lehmann and Weinberg (1997), and the effects of advertising in the cellular phone industry is empirically estimated by Danaher, Hardie, and Putsis (1998). Both normative (e.g., Bayus 1992; Padmanabhan and Bass 1993) and empirical (e.g., Speece and MacLachlan 1992; 1995; Danaher, Hardie, and Putsis 1998) research has considered the pricing decision in a product substitution setting.

As an illustration of the effects from empirically incorporating marketing mix variables in a multi-product diffusion model, let us consider price. Speece and MacLachlan (1992) extend the model in equations (5) and (6) by considering the cumulative adoption fraction to be a multiplicative function of price:
where \( G_i(P) \) is a function of the relative price of product generation \( i \). In a related paper, Speece and MacLachlan (1995) model the market potential as a multiplicative function of price, i.e., \( m_i \) in equations (5) and (6) is replaced by \( m_i G_i(P) \). In their empirical estimation of the substitution between fluid milk container packaging (glass, paper, plastic), they consider two possible specifications for the price function:

\[
G_i(P) = \left( \frac{p_i}{\hat{p}} \right)^\varepsilon \quad \text{or} \quad G_i(P) = e^{-\varepsilon \left( \frac{p_i}{\hat{p}} \right)}
\]

Here, \( p_i \) is the price of product generation \( i \), \( \hat{p} \) is the market price (i.e., average weighted price across all product generations), and \( \varepsilon \) is an estimated price sensitivity parameter.

More recently, Danaher, Hardie, and Putsis (1998) propose a multi-generation extension of the “Generalized Bass Model” (Bass, Krishnan, and Jain 1994) via a proportional hazard framework. In their model, marketing efforts \( z(t) \) affect the baseline hazard rate (i.e., the instantaneous adoption rate) in the following manner:

\[
h(t) = \frac{f(t)}{1 - F(t)} = h_0(t) e^{\beta z(t)} \quad (10)
\]

In the case of the Bass (1969) model, \( h_0(t) = p+q F_0(t) \) where \( F_0(t) \) is the baseline cumulative distribution function for the time to adoption. This model is used to empirically estimate the historical substitution patterns for cellular phones and milk containers.

**Current Status of the Literature**

Compared to other topics dealing with the diffusion of new products, it is fair to say that relatively sparse attention has been given to multi-product growth models. Our review of the
marketing literature related to this topic indicates that researchers, by and large, have only considered isolated cases of inter-product interactions. Moreover, marketing researchers have generally remained within the well-established diffusion model paradigm. Thus, extensions of the single-product diffusion model incorporate possible inter-product effects by modifying the adoption growth rate function (e.g., see equation (1)), and models of successive product generations capture these effects by adjusting the market potential of the substituting products (e.g., see equation (8)). Following the diffusion literature tradition, existing empirical research has also emphasized the fitting of historical growth patterns and analyzing the forecasting ability of the proposed model.

A CONCEPTUAL FRAMEWORK FOR MULTI-PRODUCT INTERACTIONS

In this section, we develop an expanded conceptual framework that identifies a more complete range of the possible interactions among multiple products. Our thinking on this topic is stimulated by previous work in biology (e.g., Scudo and Ziegler 1978; Moore 1993), ecology (e.g., Pielou 1977; Pianca 1983), sociology (e.g., Tuma and Hannan 1984; Brittain and Wholey 1988), and technological innovation (e.g., Farrell 1993a; b; Pistorius and Utterback 1997). We recognize that, because of complexities noted above, it is difficult to give precise definitions and boundaries for the various cases discussed in this section. Thus, our discussion is only meant to suggest both the existence and complexity of inter-product relationships. In the interests of clarity, we will discuss inter-product relationships between an existing (i.e., established or incumbent) product and a new product entrant. Our conceptual framework can, of course, be generalized to multiple products as well as situations in which the interacting products are introduced simultaneously.
As noted above, technological product substitution is a common and widely observed type of product interaction (e.g., see the seminal work by Foster 1986). “New and improved” products continually replace older, “obsolete” products. For example, in the computer industry 14-inch disk drives have eventually been replaced by 8-inch, 5.25-inch and 3.5-inch drives (and 2.5-inch drives are on the horizon). In fact, CD-ROMs have replaced many of the applications once handled by the floppy diskette. A very nice discussion of this topic and the issues faced by firms is in Christensen (1997).

In general, technological substitution implies the dominance of a new product generation over older ones. But this is rarely the case in practice. Management of a product by its producers is controllable and dynamic. While the new generation may sometimes be produced by the same firm(s) who made the older product (and be intended to obsolete it, leading perhaps to the withdrawal of the older generation from the market), this is not always the case. In some situations, producers of the older generation may be able to make changes that enhance its competitiveness in the marketplace. These improvements may take the form of product or process improvements, a lowering of price, or a product repositioning (e.g., targeting new uses and/or new users). As a consequence of such defensive actions, the existing product category may continue to survive and prosper. This can lead to long term coexistence with the competing product (this is generally termed the “sailing ship” effect, named after the sailing ship industry in which faster clipper ships were developed in response to steam-powered vessels; see Gilfillian 1935). An example is the re-emergence of cardboard packaging for milk and juice which added plastic coating (to replace wax coating) and a screw-on plastic cap (to replace the fold-away spout) in its efforts to counter the incursions by all-plastic bottles. In addition, magnetic disk storage has dramatically improved so that the growth of optical storage methods has slowed (e.g.,
Producers of the newer product may also make changes in response to the actions of the established product, resulting in *tit for tat* as the two categories compete over time. Due to the changes made possible by technology and management decisions, it is also debatable whether a new product generation is merely a variant of an old or whether it should be considered as an entirely new product category (e.g., word processing software has added features over time that were once part of desktop publishing software, entirely new features like artificial intelligence continue to be integrated into the product). If one were not privy to the similar name given the later product, one might not even recognize the two as generations of one category.

Since the new product generation affords added functionality, it may also come with a higher price tag that may serve to pay for any perceived advantages (e.g., see Figure 2). If this price difference is not managed well, it may even be possible for the new product to enhance the attractiveness of the older generation. For example, some buyers may fail to appreciate the advantages afforded by the new product or feel they are not worth the added cost. High prices and/or minimal added functionality from the new product can even enhance appreciation for the existing product among some customers (e.g., later software versions have been called “bloatware” because the added functionality is costly in terms of reduced speed and larger memory requirements; e.g., Clark and Bank 1996). Also, some buyers may accelerate their purchases of the older generation, fearing it will be withdrawn from the market. Producers have even re-introduced the older product when they realized they were losing profits (witness Coca Cola’s behavior with “New Coke”). In fact, it may be only the threat of withdrawal of the older product from the market that forces many consumers to purchase the new product.
The interactions among products can also encourage buyers of one product to better appreciate the costs and benefits afforded by a later product. For example, ownership of a pager may provide an introduction to the benefits of transportability and wireless communication, but make the buyer regret the inability to immediately return a call or speak to a caller. Thus, ownership of a pager may actually enhance a buyer’s receptivity to the added functionality of a cellular telephone. Consequently, the order of entry and the timing of entry into a marketplace may affect the sales potential of any given product (e.g., pagers may have enjoyed very different sales growth had they been introduced after cellular telephones rather than before). A domestic firm introducing its most successful USA product version as a first entry into a foreign market may experience a different level of sales than would have been the case had that version been preceded in the foreign market by the same set of previous products or generations (as was true in the domestic market).

New product failure is another type of multi-product interaction that is closely related to the technological substitution situation. In this case however, the interaction between an old and new product results in the existing product “winning” the battle. For example, in the personal computer industry the first hand-held personal digital assistants (e.g., Apple’s Newton, Bell South/IBM’s Simon, Sony’s Magic Link, Motorola’s Envoy) did not fare well against the incumbent products (e.g., see Bayus, Jain and Rao 1997 for details of the evolution of this industry). The videophone is another example of a new product that did not survive (e.g., Bulkeley 1996; Gomes 1998). Do you remember Microsoft’s Bob, a “social interface” for their Windows operating system (e.g., Clark 1995a; b)? Also, a product with poor underlying technology may impede the success of later products based on the same technology (e.g., Microsoft chairman Bill Gates has said that the Apple Newton fiasco has hindered the
development of the hand-held product category; Bayus, Jain and Rao 1997). Also a producer may not re-introduce an improved version of a failed product (e.g., Apple recently killed its Newton division) and consumers may be unduly sensitized to those aspects of the product (e.g., handwriting recognition) that were troublesome in failed versions.

*Product substitutes-in-use* is another situation in which multiple products compete for the same customers (Srivastava, Leone, and Shocker 1981). In this case, the interacting products have a negative influence on each other. Examples include desktop, laptop, and hand-held personal computers, as well as gas and electric stoves in the home appliance category. We note that product substitutes-in-use often lead to a steady-state condition in which the competing products are able to coexist in the marketplace by targeting different customer niches.

Importantly, all inter-product relationships need not be competitive. *Complementary products* can simultaneously enhance the growth prospects of each other. For example, personal computers and application software have exhibited a positive, reinforcing influence on each other for the past twenty years (e.g., Gates 1998). Complementary interactions can also be more complex in nature. Clocks and radios can be viewed as separate products, but by linking them together added functionality can be obtained (e.g., waking to music in addition to an alarm; programmability for the radio). By combining printing, faxing, scanning, and copying into one machine, a new breed of “all-in-one” machines (which have been called the “mopier”) achieve manufacturing economies by sharing components while also providing a smaller desk “footprint.” Additionally, the complementary products comprising the “all-in-one” machine enable it to compete with dedicated printers, faxes, scanners, and copiers. Depending upon pricing and quality, a buyer desiring one or only a few functions may still find the multi-function product preferable. The functions that are not needed immediately may still have value for their
potential or future utility. The fact that a buyer now owns a machine with added functionality may even provide a future incentive to learn how to make use of that latent functionality.

**Facilitating products** represent a related situation in which only one product has a positive effect on the other. In this case, the newer product exerts a positive influence on an existing product but not vice versa. Here, a “product” can be viewed as a system consisting of two or more product components in which the newer product increases the value of the established product. Desired (or really preferred) functionality is achieved by the product combination. For example, PC modems are now more desirable since they can connect with Internet sites, and microwave ovens have increased the sales of popcorn. In this case, the new product (e.g., Internet host system, microwave oven) positively influences sales of the existing product (e.g., PC modem, popcorn) by virtue of derived demand, but the reverse effect is minimal (e.g., lowering the price or promoting popcorn will not have much effect on microwave sales). In such relationships, interfaces between the product components are especially important and sales of the facilitating products are enhanced by the existence of a common standard or interface to assure compatibility and interchangeability. Sometimes the interface itself becomes another product needed to make the product system function (e.g., a car kit that lets a portable CD player play through the existing cassette player of an automobile).

**Auxiliary products** represent another form of multi-product interaction. In this case, the established product only exerts a positive influence on the new one. Here, it is the existing product that increases the value of the new product. For example, owning a personal computer positively affects the desirability of purchasing a photo scanner, but not vice versa. This concept is also much broader in scope. In some situations, this type of relationship can occur because of “training or learning.” Here, one product serves as a training device for a second (e.g., a limited
demo version of a product may whet the appetite of customers, convincing them to buy the full-featured product. Airlines’ use of full flights, high prices, uncomfortable seating, poor service, etc. may give impetus to the development of alternative means of communication such as video conferencing. The new product category may seek to imitate as much of the old as possible (e.g., in the case of video conferencing a life sized color image, motion, sound, simultaneous communication, etc. may be essential for a viable product). Their co-existence may give rise to a future predator-prey relationship (see below). Likewise, “good” technology may speed the acceptance of products employing that technology (e.g., digital technology).

Up to this point in our discussion, the inter-product relationships have either been negative or positive. However, more complex interactions that are asymmetric are also possible. Using an ecological analogy, we use the term “predator-prey” to characterize these relationships (e.g., Moore 1993). A predator-prey situation occurs when a new product (the prey), possibly employing an emerging technology, has a positive effect on the growth of an established product (the predator) and this product in turn has a negative effect on the growth of the newer product. For example, Microsoft’s PC operating system has been accused of being a predator to Netscape’s web browser functionality (e.g., Gates 1998; The Economist 1998). This attack has spurred the browser to improve its functionality to become more competitive.

On the other hand, a prey-predator situation arises when a new product (i.e., the predator) has a negative effect upon the growth of an established product (i.e., the prey), yet the existing product has a positive effect on growth of the newer product. For example, PC floppy drives have become prey for the much increased memory capabilities of the hard drive and CD-ROM. Acoustic phonographs stimulated the demand for music and home entertainment and became the prey for radio; however, eventually both were able to coexist in their own customer niches (e.g.,
Read and Welsh 1976). Attracted by the sales volumes being achieved by cassette tapes and LP records, compact discs with digital sound technology have gradually been displacing these analog products by first attacking niche markets where their long-playing and superior sound qualities would be most appreciated by buyers (e.g., classical music, motion picture soundtracks). Moreover, CD manufacturers and suppliers have been able to take advantage of the distribution channels established by the prior generation products.

Finally, we note that sometimes the relationship between products can be both that of substitute and complement. This seeming incongruity can come about because different users purchase a product for different purposes or the same user may use the product differently. For example, personal computers act as substitutes for dedicated video game systems, while at the same time personal computers are complementary to multimedia learning systems. In addition, consider products such as the 6 o’clock TV news, CNN, news-radio, news magazines (such as Time and Newsweek), the daily newspaper, news updates on the internet, etc. For some buyers, these products are substitutes because they all convey the news. Yet, since they are differentiated in terms of timeliness and depth of reporting (e.g., some are immediate while others are delayed; some only offer headlines while others offer analysis), these products can be part of a complementary portfolio of products purchased by someone with a compelling desire to be informed (e.g., McAlister 1979).

[insert Figure 3 about here]

Figure 3 summarizes the various multi-product interactions we have discussed. We note that this 3x3 matrix is only framed in terms of two products, whereas in some markets there may be more than two products that interact (e.g., a large screen monitor, color printer, modem, hard drive, CD-ROM, speakers, memory, etc. all interact in the personal computer market). In this
matrix we have included a case termed independent products. Sales of independent products do not directly affect one another. Such products are related only in the narrow sense that because they are not cost-less, their cost is a claimant on the finite monetary resources of consumers. Thus, these products have what has been termed a budget relationship that is expected to differ across consumers (e.g., Lehmann and Winer 1997).

While being more complete than previous taxonomies, the conceptual framework in Figure 3 is still limited. Importantly, Figure 3 does not directly include dynamic effects such as the changing nature of inter-product relationships over time, nor are the magnitudes of the inter-product effects directly captured (although the dotted lines in the matrix are meant to represent the “fuzzy” boundaries that exist between the various cases).

In general, it seems clear that there are two steady-state conditions for multi-product interactions: either the products end up coexisting or there is only one survivor (in the case of two interacting products). From our discussion in this section, technological product substitution and new product failure represent the cases in which only one product survives. The independent products situation is a clear-cut case in which the products coexist, although the interacting products also coexist in the complementary, facilitating, and auxiliary products cases. The product substitutes-in-use, predator-prey, and prey-predator cases can eventually lead to either steady-state condition.

Finally, product interactions may evolve over time such that the inter-product relationship changes between the various cases in Figure 3. For instance, even though the initial hand-held computers were new product failures, more recent versions may actually be auxiliary products. As technology continues to improve, these hand-held computers may eventually become product
substitutes-in-use for desktop computers. Ultimately, hand-held computers may represent a case of technological product substitution for laptop computers.

NEW DIRECTIONS FOR EMPIRICAL AND NORMATIVE RESEARCH

From our discussion so far, it is clear that the diffusion modeling literature has only considered a limited subset of the possible dynamic interactions among multiple products. Consequently, this literature has not elaborated on the various equilibrium conditions associated with the co-existence of multiple products or the survival of only a single product. More importantly, the existing literature has not considered potential strategies for the firm (or possibly competing firms) offering multiple interacting products.

In this section, we outline a class of aggregate-level dynamic models that have been used by ecologists (e.g., Pielou 1977), sociologists (e.g., Tuma and Hannan 1984), and most recently by technology researchers (e.g., Pistorius and Utterback 1997) to study interactions among several competing “population species.” This model structure seems to offer considerable promise in extending our understanding of multi-product interactions. We also sketch out some of the more interesting topics that might be pursued in future research. To simplify our discussion, in the remainder of this section we will focus on the dynamic interactions between two populations (e.g., products).

Based on numerous observations of population growth in various settings (including the laboratory and marketplace), changes in a population’s size are considered to be a general function of its size at any point in time, i.e., the dynamics of population growth are density

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4 Another promising direction of research for better understanding multi-product interactions takes an individual-level modeling approach. This stream of research is discussed in the chapter by Lattin and Roberts.
dependent. More formally, letting $x_i(t)$ represent the size of a population $i$ at time $t$, a general model structure for two interacting populations is:

$$\frac{dx_i}{dt} = x_i(t) f_i(x_i(t), x_2(t)) \quad i = 1, 2$$  \hspace{1cm} (11)

Here, the $f_i$ (the fractional growth rates associated with population $i$) are usually assumed to be a diminishing function of their respective population sizes due to finite resource limits, i.e.,

$$\frac{\partial f_i}{\partial x_i} < 0.$$  Further, $x_i(0) > 0$.

In general, changes in population $i$’s size, $\frac{dx_i}{dt}$, can be positive or negative. As a result, the general model structure in (11) has been used to study increases as well as decreases in the population of interest. In a marketing context for example, some researchers (e.g., Mahajan and Muller 1996; Kim, Chang, and Shocker 1998) have studied the number of products-in-use (e.g., an installed base of mainframe computers, a subscriber base of cellular phone users). However, often only information on sales in each time period is readily available for most markets. In such a data environment, to consider interactions among products we will let $x_i(t)$ be the cumulative sales of product $i$ up to time $t$, and therefore $\frac{dx_i}{dt}$ represents product $i$’s sales at time $t$. In this case$^5$, $x_i(t) \geq 0$ and $\frac{dx_i}{dt} \geq 0 \quad \forall t$.

$^5$ We note that the initial condition for equation (11) that $x_i(0) > 0$ does not really present any problems since the time variables can be re-scaled. More importantly, products that are not ordered before production will effectively have a sales value greater than zero at the start of its diffusion process. In practice, this occurs since firms must pre-commit to a production run of some finite size. In some cases, the firm’s initial production run is below actual demand, leading to a supply-constrained market situation. Even if a firm’s initial production run is above demand (e.g., the new product is not well received), these products will still be sold (possibly in alternative channels and/or at bargain basement prices).
Several variants of the general model structure in (11) have been previously studied, particularly linear specifications for the growth rate functions \( f_i \) (e.g., Pielou 1977; Tuma and Hannan 1984). For example, letting \( f_i(x_i) = N - a x_i(t) \) in equation (1) leads to the familiar logistic or S-shaped growth curve for a single population studied by biologists (e.g., Verhulst 1838; Gause 1934) and sociologists (e.g., Bartholomew 1973). In addition, the well-known Bass (1969) diffusion model is a special case of equation (11), as are the models discussed in Peterson and Mahajan (1978) and Norton and Bass (1987). We also note that the Lotka-Volterra predator-prey model of competing species can also be generated from equation (11), i.e.,

\[
f_1(x_2) = a - b x_2(t) \quad \text{and} \quad f_2(x_i) = -c + d x_i(t) \quad \text{(see Scudo and Ziegler 1978; Berryman 1992).}
\]

Importantly, the general model structure in (11) is very flexible since it can capture the full range of possible interactions between two populations we identify in Figure 3. For example, a situation where products are complementary is represented by the situation in which \( \frac{\partial f_1}{\partial x_2}, \frac{\partial f_2}{\partial x_1} > 0 \) and product substitutes-in-use is captured when \( \frac{\partial f_1}{\partial x_2}, \frac{\partial f_2}{\partial x_1} < 0 \). The other cases in Figure 3 can be similarly handled. We also expect that this parsimonious model structure can generate a wide range of sales patterns for these two interacting products.

Although a general solution for the non-linear differential equation system in (11) cannot explicitly be given, the qualitative behavior of this system has received extensive study. A complete mathematical treatment is in Albrecht, et.al. (1974). Under very general conditions, it has been demonstrated that the cases of complementary products and product substitutes-in-use can lead to an equilibrium situation in which both products co-exist or to a situation in which only one survives. More interestingly, for predator-prey interactions it can be shown that under
some conditions the competing populations may oscillate or cycle in sales\(^6\). Of course, the conditions for the various equilibrium solutions will depend on the functional form of the growth rate functions as well as the specific parameter values. See Pielou (1977) for a discussion and analysis of various linear formulations for the \(f_i\) functions, and see Berryman, Guitierrez, and Arditi (1995) for a discussion of several predator-prey formulations, including several ratio-dependent models (e.g., \(f_1 = a - b x_1 - c x_2; \ f_2 = d - k \frac{x_2}{x_1}\)).

As an illustration of the potential mathematical analyses that can be conducted with this model structure, let us consider the “substitute-in-use” situation. We know from our earlier discussion that this type of product interaction can eventually lead to either co-existence of both products or the survival of only one. Consistent with the prior literature (e.g., Pielou 1977), let us consider the following linear formulation:

\[
\frac{dx_1}{dt} = x_1 \left(k_1 - a_1 x_1 - \alpha x_2\right) \\
\frac{dx_2}{dt} = x_2 \left(k_2 - a_2 x_2 - \beta x_1\right)
\]  

(12) (13)

Here, \(\frac{k_i}{a_i}\) is the ultimate saturation level for product \(i\) (in the absence of any competing products) and \(\alpha, \beta\) indicate the degree of influence of one product on the other (e.g., large \(\alpha\) implies that the cumulative sales of Product 2 have a large negative effect on Product 1 sales). Note that if the two products do not interact (i.e., \(\alpha=0=\beta\)) then the cumulative sales of each product follows a logistic growth curve over time.

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\(^6\) Pistorius and Utterback (1995) present an empirical example of competing technologies that exhibit oscillatory behavior, and discuss the relationship between oscillations in a predator-prey model structure and chaotic behavior in a dynamic system.
Let us first consider the situation in which both products have nearly identical influence on each other (i.e., $\alpha=1=\beta$) and the market potential of Product 1 is greater than that of Product 2 (i.e., $\frac{k_1}{a_1} > \frac{k_2}{a_2}$). According to the "Principle of Competitive Exclusion," it can be shown that the only equilibrium solution in this case is one in which Product 1 will be the sole survivor (e.g., see Braun 1978). More generally, if $k_i > \alpha a_i \frac{k_2}{a_2}$ and $k_i > \frac{a_i k_2}{\beta a_2}$, then Product 1 will be the only survivor (i.e., the sales of Product 2 will drop to zero before Product 1 sales reaches its saturation level). On the other hand, if $\alpha a_i \frac{k_2}{a_2} < k_i < \frac{a_i k_2}{\beta a_2}$, then the two products can co-exist in the market. See Braun (1978) and Pielou (1977) for the mathematical details. Similar mathematical analyses for the other product interaction situations can be conducted to identify conditions associated with the various equilibrium states.

The general model structure of (11) can also be used to empirically study the interactions of multiple products in a defined market. For example, a general linear formulation for two products can be considered:

\[
\frac{dx_i}{dt} = x_i(t) [\lambda_i - \theta_i x_j(t) + \eta_{ij} x_j(t)] \quad i, j = 1,2; \; j \neq i.
\] (14)

Here, the three parameters to be estimated for each product are $\lambda_i$, $\theta_i$, $\eta_{ij}$ with $\lambda_i, \theta_i > 0$ ($\eta_{ij}$ can be positive, negative, or zero). We note that the significant coefficients for $\eta_{ij}$ and their signs will determine which product interaction situation is operative in the market under consideration (e.g., see Figure 3).
To empirically estimate equation (14), an exact discrete approximation can be used. As demonstrated in Tuma and Hannan (1984), the differential equation (4) can be replaced by the following difference equation (n>0 and small):\(^7\)

\[
\eta_k(t+n) = [1+n\lambda_k] \eta_k(t) - n\theta_k x^2_k(t) + n\eta_{ij} x_i(t) x_j(t).
\] (15)

Following Tuma and Hannan (1984), generalized least squares regression procedures can be used to estimate the parameters in (15) using data on cumulative sales \(x_i(t)\) for a series of discrete time periods (e.g., see Carroll 1981 for an empirical example dealing with expansion of the national education system and Brittain and Wholey 1988 for an empirical study of electronic components manufacturing). The fundamental parameters in the product interaction model (14) can then be recovered from the parameter estimates in (15). In addition, for the case of more than two product categories, nonlinear simultaneous regression methods can be used (e.g., see Kim, Chang, and Shocker 1998). These procedures take into account any error-covariances between products, and provide greater degrees of freedom than single equation approaches (thereby improving estimation efficiency). However, since simultaneous equation methods are more sensitive to multicollinearity, the chances of non-convergence are higher than in single equation approaches.

Two important extensions to the general model structure in (11) should also be noted. First, explanatory variables due to exogenous factors (e.g., marketing mix decisions, environmental conditions) can be incorporated into the model by assuming one or more of the parameters \(\lambda_i, \theta_i, \eta_{ij}\) are functions of potential causal factors. For example, \(\lambda_i\) might be replaced by \(h(y)\) in equation (14), where the vector \(y\) includes decision variables such as the price and

\(^7\)As discussed by Pielou (1977) and Tuma and Hannan (1984), there is more than one possible exact discrete approximation to equation (14). See Tuma and Hannan (1984) for the other difference equation formulations that
advertising expenditures associated with product i. In this case, the effects of marketing mix variables on the evolution of product interactions in a defined market can be empirically studied. Additionally, by defining appropriate objective functions (e.g., profit maximization, sales growth over a finite planning horizon, achieving a target market share level, etc.) potential marketing strategies of competing firms can be normatively analyzed for monopoly and duopoly situations.

Second, time varying parameters can be introduced into the general model to capture any dynamic transitions between the various situations in Figure 3 (e.g., see Bhargava 1989). For example, \( \eta_{ij} \) can be replaced by \( \eta_{ij}(t) \) in equation (14), and the resulting system of product interactions studied empirically and mathematically. We note that \( \eta_{ij}(t) \) can be a continuous or discrete (e.g., dummy variable) function. Extending the general model structure in this way will allow for a more complete understanding of the dynamics associated with multiple product interactions.

**CONCLUSIONS**

In this paper, we have reviewed the growth models that incorporate multi-product interactions and proposed some new directions for future research. These ideas are elaborated in Shocker, Kim and Bayus (1999). Our take-home message can be summarized in the following three points.

1. *Increasing our understanding of multi-product interactions represents an interesting and important topic for marketing researchers.*

By modeling the dynamics of inter-product relationships, it may be possible to obtain a better estimate of market potential of any given product and thus one can decide whether an opportunity exists for further competitive entry. Better knowledge of product interactions can
affect positioning decisions and provide needed information for product change and improvement. Worthwhile product features may be suggested by a greater understanding of the complements and substitutes to a given product. Hybrid or composite products may combine features of different categories, and by taking advantage of resulting synergies, help create new categories. Order of entry and entry timing decisions may be aided by better understanding multi-product interactions. Such understanding may help firms in entering new markets (e.g., international) with existing products and in predicting the effects of entry upon the existing products in those markets. Models of these inter-product effects might also be used to monitor the changing nature of inter-category relationships. Such models can be used to estimate the magnitudes of such effects, and by so doing affect corporate strategic monitoring. Finally, it will be important to develop approaches that can be used to estimate the possible nature of product interactions before market entry (e.g., determining which cell in Figure 3 is likely to represent the case for a particular new product entry).

(2) The current literature addressing multi-product interactions is limited in the phenomena considered, modeling approaches taken, as well as the substantive results obtained.

By incorporating the effects of related product categories, growth models can still be kept relatively simple (i.e., few parameters need to be estimated) while increasing the accuracy of forecasts made early in the life cycle of a category. It may be possible to demonstrate that forecasting accuracy is improved early in the life cycle of the new product, when least is known about its eventual market potential (e.g., as in Kim, Chang, and Shocker 1998). The set of products that serve as complements and substitutes are related. Their joint consideration may promote greater understanding of the basic combinations of benefits that drive demand for all related products. Also, the new data required may already be available, and thus require little
loss in degrees of freedom for parameter estimation. In the present paper, we have suggested
new modeling approaches built both upon the traditional marketing diffusion model and those
that incorporate ecological relationships.

(3) *Promising new directions for empirical and normative research on multi-
product interactions exist, and should be pursued in future research.*

Normative research is particularly promising. Optimal sequencing and timing of
competitive entry might be better approached through such modeling. It may also prove possible
to use multi-category models to improve parameter estimation in other models (e.g., market
potential estimates for a given category based upon a multi-category model may provide
exogenous estimates for the market potential parameter of the standard diffusion model). It
would be of considerable interest to determine the nature of related category effects upon
different model parameters (e.g., is the effect of related categories only upon market potential or
do they also effect the rates of innovation and imitation?). The idea that the market potential for
any given product is not constant, but prospectively depends upon the growth and decline of the
other preceding or co-existing product categories is particularly intriguing.

We hope this paper serves a useful role in stimulating additional research on growth
models for multi-product interactions.
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FIGURES

Figure 1: World Wide Desktop PC Sales by CPU Generation

Figure 2: Desktop PC Average (Real) Price by CPU Generation

Figure 3: A Conceptual Framework for Multi-Product Interactions
Figure 1

World Wide Desktop PC Sales by CPU Generation

UNIT SALES (millions)

YEAR

14 16 18 20 22 24 26 28 30 32

8-bit

16-bit

32-bit

8-bit

16-bit

32-bit
Figure 2

Desktop PC Average (Real) Price by CPU Generation

AVERAGE PRICE

$10,000
$8,000
$6,000
$4,000
$2,000
$0

YEAR

14 16 18 80 82 84 86 88 90 92

8-bit
16-bit
32-bit
Figure 3
A Conceptual Framework for Multi-Product Interactions

<table>
<thead>
<tr>
<th>Complementary Products</th>
<th>Facilitating Products</th>
<th>Predator-Prey Products</th>
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<tr>
<td>(e.g., PC and spreadsheet software)</td>
<td>(e.g., PC modem and Internet host system)</td>
<td>(e.g., PC operating system and web browser)</td>
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</table>

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<th>Independent Products</th>
<th>New Product Failure</th>
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<td>(i.e., budget relation only)</td>
<td>(e.g., PC and personal digital assistant)</td>
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<th>Technological Product Substitution</th>
<th>Product Substitutes-in-Use</th>
</tr>
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<td>(e.g., PC floppy drive and PC hard drive)</td>
<td>(e.g., 5.25&quot; floppy diskette and 3.5&quot; floppy diskette)</td>
<td></td>
</tr>
<tr>
<td>(e.g., Desktop PC and Laptop PC)</td>
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