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THE DYNAMICS OF COMPETITION AND OF THE DIFFUSION OF INNOVATIONS

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1 Introduction

Our purpose in this paper is to briefly review the evolution of our understanding of the emergence and diffusion of innovation, and to provide a new and more nuanced model of diffusion. Our point of departure will be to abandon the idea that innovation results only in pure competition, or a zero-sum game, between the new and the established practices. Given evidence from many cases, we believe it more likely that at least at the beginning of races between new and older products, processes and services, growth of one will often stimulate growth of the others. We will term this *symbiotic* competition. Later the interacting technologies may fall into equilibrium, or a perhaps cyclic state that we will term *predator-prey* competition, and finally a zero-sum game of *pure competition* in economic terms may ensue. This has significant implications with regard to innovation strategy.

We do not intend our work to be a forecast of technological trajectories or futures. Rather looking at generations of products, processes and services and how they evolve should help us to think systematically rather than incrementally. Thinking systematically should help us avoid the risk of lengthy and lavish overinvestment in dying businesses, which is often the case observed. Thinking systematically should also help us grasp opportunities that provide premium growth.

We will show how our model of the dynamics of competition and diffusion of innovations can be simply and practically applied and will provide a few examples analyzing the emergence of new products and services. An open source software package for determining coefficients of competition and rates of diffusion is available for interested users. The model and software do not require traditional simplifying assumptions and subsume earlier formulations and models.

2 Motivation, contributions and plan

Why is diffusion of innovation important? Ideas and inventions are major sources of both economic growth and of the expansion of human possibilities. In order for ideas to matter though, they must not only be reduced to practice, but their application must also spread or diffuse among potential users. Ideas and inventions are sometimes seen as sweeping established practices aside and somewhat hysterically as displacing or disrupting whole swathes of industry. Who though would agree that we should give up electric light and return to gas lighting or that using ice for refrigeration is more natural, convenient and efficient than an electric refrigerator and freezer? Would anyone wish to give up a mobile phone to return to land lines and pay phones?

The point is not that major adjustments were not required or that whole new industrial ecologies did not need to arise to put these new ideas into practice. Rather it is that each displacement led to broader use and possibilities for illumination, refrigeration and communication, greater efficiencies, increases in quality and much expanded markets. Moreover, the spread of electric generation and distribution networks led to many other industrial applications and household conveniences. The rise of refrigeration led to air conditioning and great expansions of cities and land values in previously oppressive climates. Mobile devices have led to the convergence of cameras, music players, maps and

location finding and a myriad of other functions and uses into a single iconic object, instead of just creating a device, which allows us to 'talk anywhere.'

How does the diffusion of new products, processes and services occur? Everett Rogers (1962) conceived of innovation as something entirely new expanding into an unoccupied market. Rogers famously described different phases in the diffusion process in which customers with different inclinations played distinct roles in sequence with earlier adopters persuading and influencing those more slowly convinced and more reluctant to adopt. Rogers' equations make the growth rate of an innovation in the market proportional to the filled niche compared to the unfilled market niche resulting in a logistic curve. Modeling diffusion thus requires an estimate of potential market size.

John Norton and Frank Bass (1987) were among the first to consider a new product or process generation replacing a prior one. Their model importantly allows for both the growth and later decline in the use of a product and assumes a growing market from generation to generation. The model has been applied simultaneously to multiple generations, such as semiconductor memory chips of increasing capacity. Norton and Bass implicitly assume that different generations of a product or device are in pure competition with one another. Thus, sales of generation one may be declining toward zero while generation two has reached its height and a new generation three is beginning to grow. Norton and Bass' model applies to many products, but as we will show later, clearly not all.

Various purely empirical efforts to estimate diffusion rates followed the early pioneers including that of John Fisher and Robert Pry of General Electric. Fisher and Pry (1971) modeled the diffusion of a new product or process becoming a substitute for a prior one as being proportional to $F/(1-F)$ plotted on a log scale, where F is the market share of the emerging product or process in question versus time. They examined dozens of cases from margarine replacing butter to basic oxygen steelmaking replacing the Bessemer process; normalized and combined their data; and fitted a function to their sample resulting again in a form of logistic curve. Assuming that all substitutions follow a similar pattern meant that for practical purposes, estimating a few parameters to fit the curve to early data would give a forecast of the full course of a substitution. Fisher and Pry make the strong claim that once a new product or process has taken three to five percent of a market, one can reliably chart the remaining rise in demand for an innovation (Fisher and Pry, 1971).

Each of the cases considered above is a highly simplified version of the world. More realistically competition to overturn relatively stable products and markets involves a welter of different alternatives coming from both familiar and unfamiliar sources and origins. Some alternative offerings enjoy increasing investment and commitment, while others drop out of the race or fill a specialized niche. In many cases innovations are put forward by newly formed firms or firms that have newly entered the competition by diversifying from an unexpected direction. An iconic historic example is the race in the computer industry in the 1970s to replace magnetic core memory (Utterback and Brown, 1972). The winner was famously semiconductor memory-chips manufactured by Intel, other newly formed firms and by several large incumbents. What is often forgotten is that this race also included a number of plausible alternatives including thin magnetic films and plated wire memories, shown in Table 1. (IBM was advancing both core memory and all three new alternatives; thus there are more entries than firms in column one).

Table 1: Computer Memory Manufacturers in 1970¹

	Established firms	New Firms
Core Memory	26	0
Plated Wire	8	0
Thin Film	5	1
Semiconductor	6*	7**
Totals	31	8

* Includes IBM and AT&T

**Includes Intel

Today we can see a similar phenomenon in the race between the long established internal combustion engine and electric vehicles (EVs). The contenders in this race include hybrid (combined gasoline and electric) vehicles, battery powered EVs and emerging hydrogen fuel cell EVs. Just to complicate matters within the hybrid category, there are pure hybrids, which run only using an electric motor with a gasoline powered motor and generator; simpler hybrids, which sometimes run electrically and sometimes mechanically; and plug in hybrids recharged occasionally from fixed charging stations and occasionally using an on-board generator. Virtually every large incumbent in the auto industry has introduced their own version of an EV, and virtually all have introduced one or more hybrid vehicles. A handful of newly formed firms have introduced only battery powered electric vehicles. Perhaps hybrid forms of products should be seen as defensive strategies of incumbents alone.

Another assumption we must remove in order to devise a better model of diffusion is the idea that innovations are independent of each other and always in *pure competition*. Rather, we will argue that modes of interaction among technologies are varied, and that new and older products, at least at the beginning of the diffusion process may experience the expansion of markets for both. If a new competitor causes the market for an established product to grow, sometimes even accelerating its growth, we will, borrowing a term from ecology, call that mode of competition *symbiosis*. A popular example appears in *Mastering the Dynamics of Innovation* (James Utterback, 1994). The first large scale and practical use of refrigeration began in the early 19th century with tools used to cut blocks of ice from ponds during the winter and store them in large insulated buildings for use over the summer months. With the development of steam-powered machines for freezing blocks of ice, year-round ice became a commodity available everywhere on demand. Far from reducing the demand for conveniently harvested ice, mechanical freezing tripled its demand while vastly expanding the use of refrigeration (Utterback, 1994, Chapter 7)!

New and established products in reality almost always influence one another in both positive and negative ways. To borrow another term from ecology, competitors often co-exist as *predators and prey*, the new products seen as predator and current product as prey. Wolves tend to prey on slower or less able deer and other herbivores, keeping their

¹ The table is constructed using data from James M. Utterback and James W. Brown, "Monitoring for Technological Opportunities," Business Horizons, October 1972, Vol. 15, 5–15.

population in check. Too small a population of wolves results in overpopulation of herbivores, which then starve for lack of food before the end of winter. Too many wolves may lead to small populations of herbivores and the starvation of wolves. Thus, wolves and herbivores coexist in an oscillating equilibrium with healthy populations of both. Predator-prey competitive modes were extensively examined and modeled (by A. J. Lotka, 1920 and by V. Volterra, 1926). We will build on their work to generalize their idea to the world of technologies, economics and markets.² To continue our example, harvested ice and machine-made ice both served ample segments of the market for refrigeration well into the 20th century and well after the appearance of electric refrigeration. Ultimately delivered ice entered pure competition with electric refrigeration and retreated to small and specialized niches in the market.

In sum, modes of competition need not be unitary, but one mode may evolve into another over time. In general, it is a dynamic process. In the examples we have studied in some detail it is tempting to speculate that we may see symbiosis first; later evolving to a form of predator prey interaction (with either the old or new product dominant for a period of time); followed by the emergence of pure competition with the extinction of one or the other.

The main contributions of this work are the following:

- 1) We have developed a model for the diffusion of technology not just for head to head competition but also for alternative competitive modes such as predators (N) and prey (M) in equilibrium and in symbiosis.
- 2) The model provides for analysis of diffusion not simply of one new product (N) contending with one established product (M), but rather for multiple M_i and N_j .
- 3) Earlier models such as those presented by Rogers and by Norton and Bass can be readily shown to be special cases of our more general equations.
- 4) By relaxing the necessity of assuming pure competition, changing modes of competition can be calculated year by year as they evolve.
- 5) Similarly, by relaxing the need to estimate a total market or niche size in advance, market penetration can be calculated year by year as it evolves.
- 6) We provide easily used software for analysis, publicly available and updated, in a widely understood simulation language.
- 7) The model is realistically path dependent providing varying results depending on the starting point of each competition, and this can be represented visually in a phase diagram, at least for the two-dimensional M vs. N product case.
- 8) By using our software and model and analyzing 50 years of data from engineered wood products industry, we show a practical case study of how the “mode” of competition changes in an expected pattern.

Although the term *competition* is frequently used in the context of innovation and industrial economics an exact description of the term is not usually explicitly given. The interaction between technologies is often not one of competition in the strict sense of the word, as there are many cases where technologies interact in a relationship, which is not necessarily confrontational. The multi-mode approach for interaction among technologies provides a useful framework within which to understand and apply this richer landscape of interaction.

² The analogy is not perfect of course, as deer do not eat wolves.

Not only do the multiple modes provide the flexibility to examine interaction in the various circumstances where the different technologies inhibit and enhance one another's growth, i.e. in the three distinct modes described below, but it also allows one to account for the transitional effects as the interaction between the technologies transgresses from one mode to another with time. The notion that the modes of interaction between two technologies can change with time is one of the main points that differentiate the technological framework proposed here from similar natural ecological frameworks.

By considering the possibility that one technology may either enhance or inhibit another technology's growth, one finds that three possible modes of interaction can exist, viz. *pure competition* where both technologies *inhibit* the other's growth rate, *symbiosis* where both technologies *enhance* the other's growth rate and *predator-prey interaction* where one technology *enhances* the other's growth rate but the second *inhibits* the growth rate of the first. Although such frameworks had, of course, been successfully applied in the fields of biological ecology (Pianka, 1983) and organizational ecology (Brittain and Wholey, 1988) a survey of the literature circa early 1994 showed then that with regard to *technologies*, pure competition was often discussed, symbiosis sometimes referred to but that predator-prey interaction between technologies was very rarely mentioned (Pianka, 1983 in Carroll (Ed.), 1988).

The multi-mode framework is illustrated in Figure 1 for the case of two technologies. In principle, the framework can be extended to any finite number of technologies. Note that although there are three modes, two possible predator-prey interactions are indicated (depending on which technology is the predator and which the prey), and hence four possible types of interaction. In developing our model in the following section, however, we shall refer to three distinct modes.

		Effect of A on B's growth rate	
		Positive	Negative
Effect of B on A's growth rate	Positive	Symbiosis	Predator (A) – Prey (B)
	Negative	Predator (B) – Prey (A)	Pure competition

Figure 1: Multi-mode framework for the interaction among two technologies

In principle, there are more modes if the cases where one technology has zero impact on the other. For the purpose of our discussion, we can consider those to be special cases, and discuss the interaction with the three modes shown in Table 2.

Once the multi-mode framework has been formulated, the next step is to develop a mathematical model. One of the first challenges is to find a metric which defines the concepts of 'competition', and 'good for one another or not', with mathematical rigor rather than just as qualitative concepts. The concept of *growth rate* offers itself as a suitable and appropriate way of classifying the process of interaction among technologies, so that in general, *interaction* can be manifested in the concept of the reciprocal effect that one technology has on another's growth rate.

The following section discusses a mathematical model, which can be used to describe and simulate a framework for multi-mode interaction among technologies described in the previous section. In the third section we will present an extended example simulating the

diffusion and interaction of two products over the entire life of a new product from birth to maturity.

Our original contribution here is to present and illustrate the use of a Matlab³ program based on our model developed by Yilmaz, specifically for modeling the multi-mode framework for interaction among technologies. This program has been successfully applied to model the dynamics, and also has the ability to estimate parameters of the LV equations over 50 years by also finding the mode of interactions for the first time.

In the fourth section we will consider strategic and tactical applications of our model and suggest directions for future research.

3 A modified LV system for multi-mode interaction among technologies⁴

Our general model of the diffusion of innovation is based on the Lotka-Volterra (LV) equations, originally developed and applied to biological and ecological systems. This section of the paper is based on research conducted by the authors at MIT in early 1994, and draws heavily on a number of papers and conference proceedings in which the work was originally published. The authors presented more details of the mathematical modeling underpinning the multi-mode framework in 1994 (Pistorius and Utterback, 1996).⁵ A paper (Pistorius and Utterback, 1995) focused on mortality indicators for mature technologies. The paper setting out the fundamentals of the multi-mode framework was published a year later (Pistorius and Utterback, 1997). A number of researchers have since concluded that the LV model exhibits superior performance vis-à-vis other models.

The concept of substitution inherently implies that two (or more) technologies are competing, and that one is displacing the other. However, traditional substitution models such as the Fisher-Pry model, and related but more sophisticated models, presented the dilemma that they did not model two technologies competing against each other, but rather one technology competing against a saturated market or market potential. Due to the fact that a single equation describes the system, the new technology and the rest of the market are coupled in one equation with a few parameters accounting for the adoption of the new technology. Such a formulation yields a solution where the growth of the new technology is accompanied by the decline of the old (given that the size of the market niche stays constant). Single equation formulations do not offer a solution where the older technologies, represented by the market, has a chance of independently “fighting back”.

Grübler comments that "... It appears that much of the debate on the appropriate mathematical model(s) of diffusion, in particular the question of symmetrical versus asymmetrical models, may be the result of looking at innovation from a unary (i.e., an innovation grows into a vacuum) or a binary (the market share of an innovation is analyzed *vis-a-vis* the remainder of the competing technologies) perspective. However, diffusion

³ MatLab is a registered trade name. An open source version of our software will soon be available.

⁴ C.W.I Pistorius, "A growth related, multi-mode framework for interaction among technologies", SM thesis, Alfred P Sloan School of Management, Massachusetts Institute of Technology, 1994. Supervisor: J.M. Utterback. Available at: <http://hdl.handle.net/1721.1/12081>

⁵ The paper is also available as an MIT working paper at: https://www.researchgate.net/profile/James_Utterback/publication/5176207_A_Lotka-Volterra_model_for_multi-mode_technological_interaction_modelling_competition_symbiosis_and_predator_prey_modes/links/543ffec0cf21227a11ba015.pdf

phenomena generally call for a multivariate approach, which has not yet found wide application in the various diffusion disciplines.” In the general case, one often finds that multiple technologies are vying for market share at the same time and that more than one technology can be growing market share at the same time (Grübler, 1991).

The differential equation(s) describing the diffusion of a technology must be based on the underlying mechanisms involved. In order to model the diffusion characteristics of a technology, it is therefore necessary that the extent of the resources available be taken into account. Finite resources are often embodied in a market niche of finite size. A single equation cannot, however, describe the growth and competition of two technologies simultaneously for it does not account for their respective effects on one another. It can at best model the diffusion of one technology into a market (Carroll, 1981). To model the competition of two technologies, one would need to set up a differential equation for each of the technologies based on the underlying drivers and inhibitors for that technology, together with coupling coefficients that reflect the technologies’ effect on one another’s growth rate. In order to address the problem at hand, it is necessary to model both the technologies explicitly, each with its own equation. They must then be coupled with coupling coefficients to account for the interaction between them.

In order to mathematically model the multi-mode framework for interaction among technologies, the traditional and classic substitution models, which are based on single equation formulas, are hence not fit for purpose. It is necessary to model all the technologies, each with its own equation, although they must be coupled with coupling coefficients to account for the interaction between them. A *system of coupled differential equations* is therefore required, with each technology represented by its own equation and coupling between them.

A system that is applicable to this problem (albeit in modified form) was formulated some time ago by the ecologists Lotka and Volterra, known as the *Lotka-Volterra (LV) equations*. Several authors have shown that the Lotka-Volterra equations can be successfully applied to model technological diffusion, (among them Bhargava, 1989; Farrell, 1993; Marchetti, 1987; Modis, 1992; Nakićenović, 1979; and as quoted by Marchetti, 1987; and Porter *et al.*, 1991) This is an important observation and we accepted their success as additional justification for pursuing the line of reasoning in the development of this the model. Several authors have shown or commented on the fact that the Lotka-Volterra equations can be successfully applied to model technological diffusion. Marchetti, for example, notes that “... I am fairly convinced that the equations Volterra developed for ecological systems are very good descriptors of human affairs. In a nutshell, I suppose that the social system can be reduced to structures that compete in a Darwinian way, their flow and ebb being described by the Volterra equations, the simplest solution of which is a logistic” (Marchetti, 1983).

The reader should take note that the nomenclature *Lotka-Volterra equations* had come to be used to indicate pure competitive as well as predator-prey systems, often without explicitly stating which case is being modeled since it is probably assumed that it should be clear from the context. As shown below, the formulations of the Lotka-Volterra equations for the different modes are different (specifically regarding the positive/negative sign of the coupling coefficient) and hence have very different characteristics.

In order to understand the fundamentals of the LV system, it is helpful to start with basic logistic growth. The differential equation which underlies this can be expressed as (Girifalco,1991):

$$\frac{dN}{dt} = aN - bN^2 \quad (1a)$$

This equation results in the familiar S-curve for $N(t)$, shown in Figure 2. It is useful to investigate the physical interpretation of the individual terms in this equation, as it supports the understanding of the modified LV equations for multi-mode interaction introduced later.

The first term (aN) fuels exponential growth, where the growth rate at any given time is proportional to the number at that time. Hence the more there are, the faster the growth. This is shown in equation (1b), where N_0 is a constant indicating the initial condition.

$$N(t) = N_0 e^{at} \quad (1b)$$

Very often however, growth is constrained by limited resources. In such an environment, the individual elements vie with one another (competition) for the resources. The vying interaction is modeled by the term N^2 . This indicates interaction of elements of the population with one another, and has a negative effect on the growth rate. The term bN^2 is thus subtracted, or ' $-bN^2$ ' added to the equation, to account for this restriction, leading to the formulation in (1a). In (1b), it is silently assumed that there is no constraint on resources, hence there is assumed to be no vying or competition amongst members of the population so that $b=0$.

The solution of (1a) is the well-known S-curve,

$$N(t) = \frac{a/b}{1 + e^{a(t_0 - t)}} \quad (1c)$$

Figure 2 below shows a typical S-curve (with arbitrarily chosen parameters). The upper limit of growth is a/b and t_0 is the time at which the "halfway" mark (i.e. half the value of the upper limit) is reached. Note how in this case the halfway mark ($a/2b=7.5$) is reached at $t_0=50$ and the limit ($a/b=15$) is approached as time progresses.

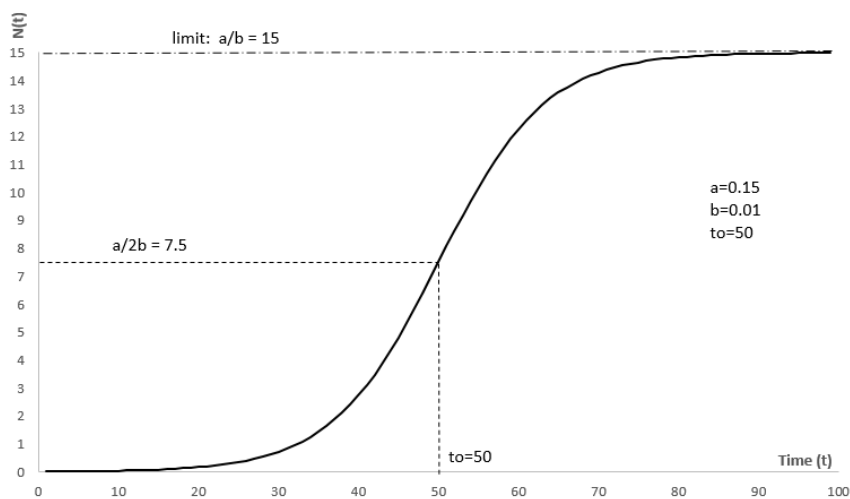


Figure 2: Typical S-curve

3.1 Lotka-Volterra equations for ecological systems

The premise of the Lotka-Volterra system is that each population ('species') is represented by its own equation similar to (1a) in the absence of its interaction with another population. When two or more populations start interacting, a term representing this interaction is then added to each equation.

Consider an ecological system where N represents the predator population and M represents the prey population. In this case, the system of equations representing the dynamics of the total population ($N+M$) will be (Carroll, 1981):

$$\frac{dN}{dt} = a_n N - b_n N^2 + c_{nm} NM \quad (2a)$$

and

$$\frac{dM}{dt} = a_m M - b_m M^2 + c_{mn} MN \quad (2b)$$

where in this case $c_{nm} > 0$ and $c_{mn} < 0$. See also Note 1 regarding conventions pertaining to the signs of coefficients.

The terms NM and MN indicate elements of the two different species interacting with one another. In these equations, the terms NM and MN have similar forms and functions as N^2 and M^2 , except that they represent elements of the two different populations interacting with one another rather than elements of the same interacting with itself.

Equation (2) clearly indicates a predator-prey relationship. Since $c_{nm} > 0$, interaction between elements of N (predator) and M (prey) will enhance the growth rate of the predator (N). Similarly, since $c_{mn} < 0$, interaction between N and M will have a negative effect on the growth rate of the prey (M).

The nature of ecological populations is such that the c_{nm} and c_{mn} coefficients will always retain their sign. Mother Nature has mandated that the wolf will always hunt the deer and never the other way around. Hence the relationship between lion and antelope will always be predator-prey, with wolf the predator and deer the prey. As we will show, this is not necessarily the case with technologies, where the mode of interaction can change with time, as can the roles of predator and the prey.

For the moment we are also assuming that the coefficients (a, b, c) are constants. However, that does not necessarily have to be so. In the case of technological interaction, it is conceivable that the coefficients may indeed change with time. We return to this issue again later.

3.2 Lotka-Volterra equations for multi-mode technology interaction

The ecological predator-prey equations in Equation (2) can now be modified so they can be used to represent pure competition, symbiosis and predator-prey relationships in a formulation to model the multi-mode framework for the interaction among technologies. The modification is vested in allowing the signs of the c -coefficients to be able to change, and is shown later, for the coefficients to be time dependent rather than constants.

For two technologies, the modified formulation will thus be

$$\frac{dN}{dt} = a_n N - b_n N^2 + c_{nm} NM \quad (3a)$$

and

$$\frac{dM}{dt} = a_m M - b_m M^2 + c_{mn} MN \quad (3b)$$

where the distinction between the different modes is indicated by whether the c -coefficients are positive or negative, as indicated in Table 2. As noted before, $c=0$ cases can be considered as distinct modes in their own right.

		Effect of N on M's growth rate	
		Positive	Negative
Effect of M on N's growth rate	Positive	Symbiosis $c_{nm} > 0$ and $c_{mn} > 0$	Predator (N) – Prey (M) $c_{nm} > 0$ and $c_{mn} < 0$
	Negative	Predator (M) – Prey (N) $c_{nm} > 0$ and $c_{mn} < 0$	Pure competition $c_{nm} < 0$ and $c_{mn} < 0$

Table 2: Signs of c -coefficients in modified LV equations, designating interaction modes

Note 1: The signs of the c -coefficients

The authors' original research and papers (1994-1997) used the convention where the coefficients c_{nm} and c_{mn} were assumed to be always positive, with the distinction between modes indicated by \pm signs preceding the c -coefficients. This followed the convention of the original ecological LV equations and supports and intuitive understanding of the LV system. Hence (3b) was originally expressed as

$$\frac{dM}{dt} = a_m M - b_m M^2 \pm c_{mn} MN$$

with c_{mn} always positive and the preceding sign (\pm) indicating the mode (and similarly for (3a)).

Although there is nothing wrong with this from a convention viewpoint, it later became apparent that a convention where '+' signs precede the c -coefficients and the c -coefficients themselves are allowed to be positive or negative has advantages when programs such as Matlab are used to solve the equations. The programs can then also be used to estimate the coefficients *as well as whether they are positive or negative*. This is a very powerful concept. Given a data set, the numerical solution will yield not only the intensity of the interaction (numerical value of the coefficients), but also the mode of interaction (reflected in whether the coefficient estimated is positive or negative).

3.3 An iterative solution for the modified Lotka-Volterra equations

Although there are several statements in the literature indicating that the Lotka-Volterra equations and particularly the pure competition formulation cannot be solved explicitly (see for example Porter, *et al*, 1991; Hannan and Freeman, 1989), they can be solved numerically. The authors adapted Pielou's formulation in difference form for the case of pure competition (Pielou, 1969). By accounting for the appropriate sign changes (associated with the c -coefficients), Pielou's solution for the pure competitive case was then duly modified to yield solutions for the other modes as well⁶.

At this point, we revert back to our original convention that $c > 0$, with the preceding signs explicitly indicated as '+' or '-' (see Note 2). For illustrative purposes, this has the advantage of clearly illustrating the mode of interaction.

The modified solution for two technologies in a predator-prey mode where N is the predator and M the prey, thus becomes

$$N(t + 1) = \frac{\alpha_n N(t)}{1 + \beta_n N(t) - \left(\frac{c_{nm}}{b_n}\right) \beta_n M(t)} \quad (4a)$$

where

$$\alpha_n = e^{a_n} \quad (4b)$$

$$\beta_n = \frac{b_n(\alpha_n - 1)}{a_n} \quad (4c)$$

and

$$M(t + 1) = \frac{\alpha_m M(t)}{1 + \beta_m M(t) + \left(\frac{c_{mn}}{b_m}\right) \beta_m N(t)} \quad (5a)$$

where

$$\alpha_m = e^{a_m} \quad (5b)$$

$$\beta_m = \frac{b_m(\alpha_m - 1)}{a_m} \quad (5c)$$

Note that difference in signs preceding the third term in the denominators. This determines N to be the predator and M to be the prey.

3.4 A general solution for multi-mode interaction among technologies

Consider now J technologies interacting in the same market niche, and let $T_i(t)$ represent technology i with $(1 \leq i \leq J)$.

The differential equation for $T_i(t)$ can be expressed as

⁶ Later papers by other researchers also referred to a solution offered by Leslie (Leslie, P.H., "A stochastic model for studying the properties of certain biological systems by numerical methods", *Biometrika*, 45 (1957) 16-31).

$$\frac{dT_i}{dt} = a_i T_i + \sum_{j=1}^J s_{ij} c_{ij} T_i T_j \quad (6)$$

where all coefficients are positive (see Note 2) and $s_{ij}c_{ij} = -b_i$. Furthermore, $s_{ij} = +1$ if technology j has a positive influence on technology i 's growth, whereas $s_{ij} = -1$ if technology j has a negative influence on technology i 's growth. Marchetti (1987), Hannan and Freeman (1989) and Modis (1993) among others, have suggested similar sets of equations. However, at the time, they seemed to refer only to the case of pure competition (and not the multiple modes presented here). They did not offer solutions for the equations and specifically not for the multi-technology case.

The difference form solution for $T_i(t)$ can be found by extending Pielou's solution to the general case, i.e.

$$T_i(t+1) = \frac{e^{a_i T_i(t)}}{1 - \sum_{j=1}^J \frac{s_{ij} c_{ij} (e^{a_i - 1})}{a_i} T_j(t)} \quad (7)$$

This formulation is a general solution for multi-technology, multi-mode interaction. It can be used to model the interaction of any finite number of technologies where the interaction among any pair can either be pure competition, predator-prey or symbiosis.⁷

4 Dynamics of Competitive Modes

Plywood, probably the first wood composite was first produced as a specialty in the late 1800s. Plywood's value in a wider range of uses became clear during the Second World War, and demand rose rapidly afterward. Production economics and quality depended importantly on the supply of large straight trees with trunks free of knots and defects needed for making veneer. By 1980 the supply of adequate trees had diminished and their price had risen by sixty-percent in just five years while quality was in vivid decline. Inferior substitutes for plywood such as wafer-board were being tried in some applications. Research by Henry Montrey describes the resulting challenges to the forest-products industry and its customers. His masters' thesis (1982) embodied a deep analysis of both new composite panel options and the plywood panels they might replace in various market segments and new segments. Also covered were technical properties, production processes and economics, and market conditions serving as both incentives and barriers to the adoption of the new composite materials.

A particular experimental composite, made of oriented and layered strands, peeled from widely available smaller trees (Oriented Strand Board, or OSB) was under development. Oriented Strand Board would clearly make more efficient use of a wider variety of forest resources and not just the perfect, large and diminishing old trees required for plywood.

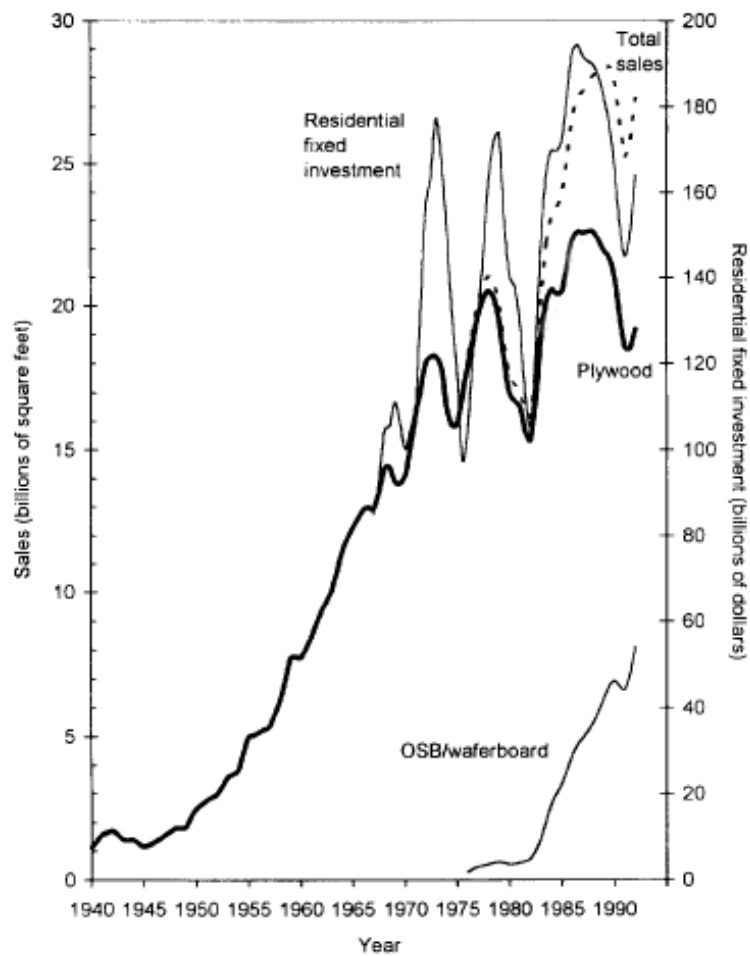
⁷ The useful application of this formulation has since been overtaken by developments in software packages, which have the ability to solve complex sets of differential equations. The results below were obtained by Yilmaz. He used the solver algorithms embedded in Matlab (a registered trademark of Mathworks, Inc.) to solve the equations and also to estimate the coefficients and their signs.

Moreover, the resulting panels were less expensive, stronger and stiffer than plywood of equal thickness making them perfect for use under flooring, roofing and siding, among the major markets for plywood. In 1990 Montrey extended the data from his thesis, compared the early growth of composite panels to the growth of plywood decades earlier, presented the result, and challenged industry leaders to ask why composites would not be at least as successful an innovation. The forecast presented showed expected growth for composites to at least equal the historic early rapid growth of plywood, the industry's greatest success to date in improving properties and cost (Montrey and Utterback, 1990). Montrey's forecast helped remove arguments against the consideration of the new panels. In retrospect his analysis, then seen as optimistic, was actually too conservative. It is often easier to see the weaknesses in new ideas judged against current practice, than it is to see their potential strengths and the new values that they alone may offer. His data are shown below with residential fixed investment added. One can see in Figure 3 below that fluctuations in investment fell almost entirely on plywood sales while sales of composite panels grew steadily (Pistorius and Utterback, 1995).

A perplexing question is, "why, when faced with superior new alternatives, large and long lived competitors resist change?" They are actually often seen to continue investing in and improving older alternating long beyond the point when that makes any economic or strategic sense (Foster, 1986). A pervasive view of competition is to view competition as a zero sum game. We are socialized toward a zero sum view from our earliest experiences with competitive games, the satisfaction of winning and the pain of losing. Who might remember the second pilot to fly alone across the Atlantic Ocean?

In sum, modes of competition need not be unitary, but one mode may evolve into another over time. In general, it is a dynamic process. In the examples we have studied in some detail it is tempting to speculate that we may see symbiosis first; later evolving to a form of predator prey interaction (with either the old or new product dominant for a period of time); followed by the emergence of pure competition with the extinction of one or the other.

Figure 3: U.S. Sales of Plywood and Composite Panels (in constant 1992 Dollars)



In a provocative new analysis of five decades (1964-2014) of sales data in Table 3 and Figure 4 below, Erdem Yilmaz has clearly shown the dynamics of changing modes in this example over time from symbiosis (through 1973) to predator-prey (through 1999) and finally competition as expected. This analysis demonstrates the importance of considering the mode of competition in building a scenario. (Each calculation of competitive mode is a decadal average from his simulation). Though this is just a single example from a 50-year analysis of the plywood versus OSB competition, it conforms with our hypothesis. We will point below to similar examples such as harvested and machine-made ice as precedents.

Years	Type Of Relationship	Plywood on OSB	OSB on Plywood	Goodness of fit
1964 to 1973	Symbiotic	1.16E-05	1.85E-05	
1965 to 1974	Symbiotic	9.86E-06	9.82E-06	
1966 to 1975	Symbiotic	7.72E-06	6.28E-06	
1967 to 1976	Symbiotic	7.38E-06	7.02E-06	
1968 to 1977	Symbiotic	5.76E-06	3.13E-06	
1969 to 1978	Symbiotic	5.03E-06	4.93E-06	
1970 to 1979	Symbiotic	5.10E-06	4.20E-06	
1971 to 1980	Predator-Prey	2.72E-06	-1.19E-06	
1972 to 1981	Predator-Prey	6.41E-07	-3.87E-06	
1973 to 1982	Competition	-3.72E-07	-3.89E-06	
1974 to 1983	Symbiotic	1.02E-06	1.51E-06	
1975 to 1984	Symbiotic	3.08E-06	2.84E-06	
1976 to 1985	Predator-Prey	1.30E-06	-3.65E-07	
1977 to 1986	Predator-Prey	3.40E-07	-1.43E-06	
1978 to 1987	Symbiotic	5.81E-07	1.58E-07	
1979 to 1988	Symbiotic	2.16E-06	1.37E-06	
1980 to 1989	Symbiotic	4.15E-06	4.27E-06	
1981 to 1990	Symbiotic	4.72E-06	2.31E-06	
1982 to 1991	Symbiotic	6.08E-06	2.67E-06	
1983 to 1992	Predator-Prey	4.00E-06	-5.77E-07	
1984 to 1993	Predator-Prey	3.06E-06	-8.11E-07	
1985 to 1994	Predator-Prey	3.05E-06	-1.12E-06	
1986 to 1995	Predator-Prey	2.64E-06	-2.13E-06	
1987 to 1996	Predator-Prey	2.55E-06	-2.32E-06	
1988 to 1997	Predator-Prey	2.77E-06	-1.84E-06	
1989 to 1998	Predator-Prey	3.09E-06	-1.13E-06	
1990 to 1999	Predator-Prey	3.71E-06	-2.88E-07	
1991 to 2000	Symbiotic	4.64E-06	7.93E-07	
1992 to 2001	Symbiotic	3.56E-06	4.39E-07	
1993 to 2002	Symbiotic	3.27E-06	3.86E-07	
1994 to 2003	Symbiotic	3.12E-06	3.08E-07	
1995 to 2004	Symbiotic	3.61E-06	1.06E-06	
1996 to 2005	Symbiotic	2.69E-06	9.34E-08	
1997 to 2006	Symbiotic	2.38E-06	3.12E-07	
1998 to 2007	Predator-Prey	1.36E-06	-6.69E-08	
1999 to 2008	Competition	-3.33E-07	-7.04E-07	
2000 to 2009	Competition	-1.29E-06	-1.23E-06	
2001 to 2010	Competition	-1.55E-06	-1.48E-06	
2002 to 2011	Competition	-2.28E-06	-2.07E-06	
2003 to 2012	Competition	-3.85E-06	-2.29E-06	
2004 to 2013	Competition	-4.80E-06	-3.14E-06	

Table 3: Magnitudes and of modes of competition between OSB and Plywood, 1964-2014⁸

In Table 3, “Type of Relationship” shows the mode of interaction between technologies. “Plywood on OSB” is the coefficient representing the impact of decrease or increase of Plywood’s market size to the one of OSB.⁹ In columns 3 and 4, blue color represents a positive impact whereas red color represents a negative impact. Length of the horizontal bars represents the strength of the coefficient. “OSB on Plywood” is the coefficient representing the impact of decrease or increase of OSB’s market size to the one of plywood. “Goodness of fit” is the coefficient representing how well the model matches with the

⁸ UNECE/FAO TIMBER database, 1964-2014

⁹ The results here are slightly different than those mentioned earlier, as the UNECE/FAO database lumps the diminishing sales of wafer board with those of OSB.

actual data. Length of the horizontal bars represents how well the model matches to the data in the corresponding decade.

Figure 4: Effect of N on M's growth rate C_{nm} and M on N's growth rate C_{mn}

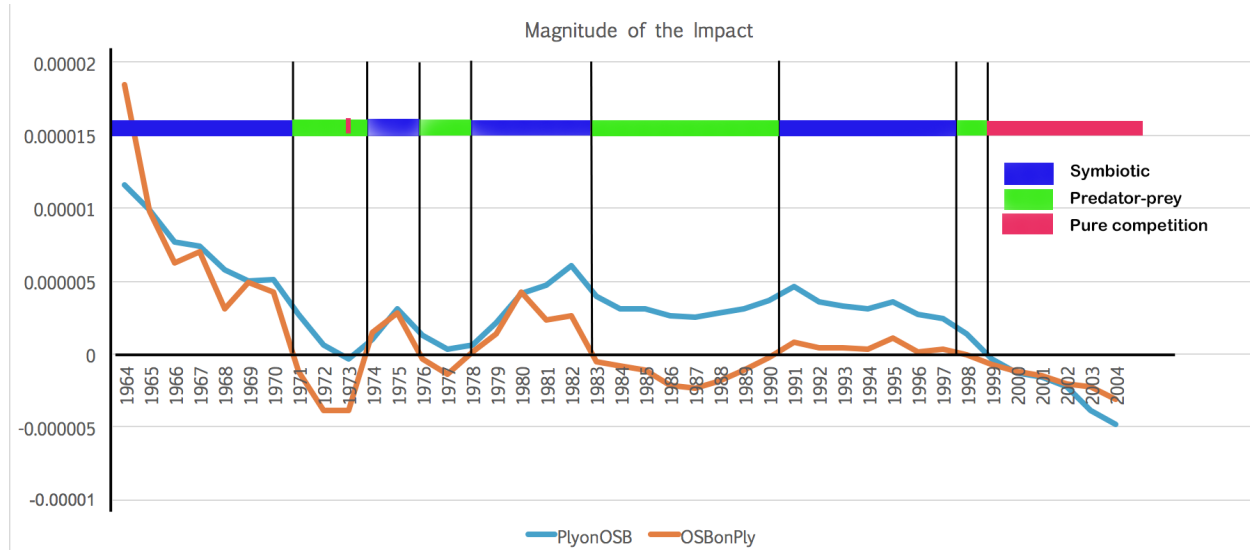


Figure 4 tells a compelling story. Coefficients of each decade with the indicated starting year are shown. Plywood's impact on OSB is shown in blue color and OSB's impact on plywood is shown with red. The relationship ("mode of interaction") is evident from the sign of the coefficient. In the early years, we observe that the magnitude of interaction is at its peak compared to the following years. The magnitude of the impact is observed to shrink over the years.

The results are impressive. Not only as they apply to this specific case, but in general showing how the interaction modes change over time. Many researchers (including ourselves) have postulated that this happens, but we cannot recall having come across similar results – based on data - which show the dynamic nature of the relationship, with the interaction changing from symbiosis to predator-prey to pure competition as time evolves. The underlying issue here is that the coefficients change with time – most of the models just assume that the coefficients are constants. The fact that the coefficients change with time has significant implications for application in innovation strategy.

Prior reports have observed oscillations in market share during product competitions (including Marchetti, 1983; Modis and Debecker, 1992; and Modis, 1992, 1993) and have suggested that the fluctuations become random or chaotic when populations or markets approach saturation. Montrey and Utterback, (Montrey and Utterback 1990) suggest that oscillations may indicate the emergence of a new technology and the demise of the old. Referring to the oscillations in the mature phase of plywood's growth they state, "we venture to hypothesize that the type of variance in the production of a commodity such as shown for plywood in recent years... is a clear sign of the vulnerability of the product to an emerging substitution." In the case of OSB and plywood we have one can observe that the oscillations of sales of plywood shown in Figure 3 seem to match fluctuations in residential fixed investment. Comparing Figure 3 with figure 4 one can see that each time construction

diminished the competitive mode shifted from symbiosis to predator-prey with OSB being the predator taking sales from plywood. When construction rebounds symbiosis seems to return. Of course such matching of possible causes to outcomes after the fact do not rule out other possibilities or even not relationship at all. They suggest though that variations in diffusion and competition may well be stimulated by factors both within and beyond the system of producers and consumers. Hastings, et al., (2018) suggest both possibilities based on their recent analysis of studies of ecological systems in nature.

Outside stimuli might include economic cycles; regulatory and policy changes; unexpected shifts in technology; and resource shortages. We have seen all of these in the extended case discussed. Ups and downs in the building cycle largely affected only the demand for plywood. Changes from product to performance specifications allowed OSB to be used freely in most plywood market segments and opened some new ones. Growing shortages of large logs led to experiments with composite products in a government laboratory with OSB proving to be both stronger and less expensive to produce than plywood. Internal system stimuli might include large and discontinuous expansions of production capacity (Tang and Zannetos, 1986); opening of a new market niche or stream (Penrose, 1959); and radical product innovations and substitutions (Cornwall, 2016; Hughes, 2019).

One of the key insights from this simulation was recognizing that the computer simulation could not only estimate the absolute value of the coefficients, but also their sign. This is the key, which indicates the nature of the relationship and the mode of interaction. The amplitude of the coefficient indicates the 'strength' of the interaction relationship and the sign the nature of the relationship (pure competition, symbiosis or predator-prey) at a given point in time.

The authors believe that these findings open a very rich field of enquiry to explain why the modes and how the modes appear, and also the sequence in which the modes follow one another – first symbiotic, then predator-prey, and eventually competition. Also, there seems to be a cyclic change between symbiosis and predator-prey modes, until the competition mode finally emerges. It is interesting to note that, in this case, OSB is always the predator in the predator-prey phase.

We make a number of observations from this analysis, viz.

- Oriented Strand Board based products start their market penetration with a symbiotic relationship with the incumbent plywood products. This phenomenon aligned with our expectation, as we believe products of emerging technologies diffuse in the market with the help of incumbents and new technologies help incumbents.
- The strength of the symbiotic effect decays over time. Between years 1964 to 1977, we observe a symbiotic relationship, which decays with time.
- The interactions then change from symbiotic to predator-prey, but we continue to observe some periods where the interaction is symbiotic. As shown in Table 3 (red marks on 4th column) OSB products are predators and the incumbent plywood products, the prey. Even though we observe symbiotic relationships later in the analysis, in these cases (1991-2007), OSB's impact on plywood is near zero and not far from a predator prey.

- In the last part of the analysis, we observe pure competition to be the dominant mode of interaction. The strength of the competition increases over time. This however could be due to strong external impacts.
- Figure 4 shows the diminishing amplitude of the coefficients.

By relaxing the constraints imposed by limited amounts of high-quality raw materials, composite products have fueled the renaissance of wood-based building techniques and enabled an expansion of forest products use in construction extending remarkably to high-rise buildings.

5. Implications for strategy and future research

The authors suggest that this work is of more than academic interest, and has significant implications for innovation strategy. The theory and findings can be useful for the developers of new, emerging and "disruptive" technologies as well as the defenders of mature technologies in understanding how the interactions of the various technologies influence the trajectories of others. An important aspect of innovation strategy pertains to the decisions of when to adopt a new technology, abandon the old or pursue an interim approach.

The fact that the interaction among technologies is not unitary but in fact can exist in a number of modes (symbiosis, predator-prey and pure competition), mandates that each of the modes will require a different strategy for each of the players. Furthermore, as we have shown, the interaction modes change dynamically, i.e. the nature of interaction of one technology with another can (and does) change from one mode to another as time progresses. In the example of Plywood/OSB, the interaction starts off in a symbiotic mode, where the emerging technology (OSB) stimulates growth in the mature technology (plywood). A cyclical pattern then follows, which includes predator-prey modes where plywood (as the prey) stimulates growth in OSB (the predator), but OSB has a negative effect on the diffusion of plywood. Finally, a mode of pure competition emerges where each of the technologies has a negative effect on the other.

Strategies are invariably based on underlying assumptions, often implicit. If innovation strategies and strategic decisions are based on invalid assumptions regarding the way technologies interact, one should not be surprised if results ranging from "less than ideal" to catastrophic follow. Should, for example, management not appreciate that the nature of the interaction among technologies is multi-modal and furthermore that the modes change dynamically, it is foreseeable that they will deploy a 'constant' strategy, which may be 'perfect' for the presumed assumptions, but not for the actual modes their technology is in interacting with others.

Consider for example, the case where a mature product starts to experience a growth spurt, while at the same time the managers detect the emergence of a potentially threatening technology. One can easily see that a 'single and constant mode' mindset of management may assume that the growth may be due to other causes (which of course it may) and merely relish the new growth, or that the new technology is nothing to worry about. In fact, as our analysis shows, the growth spurt may be a lead indicator that what is now a symbiotic relationship may soon change to predator-prey and then to pure competition. Had the management realized this, they would (or should) probably adopt a very different strategy.

It is tempting to think that strategic challenges will come from familiar sources and competitors, but truly transforming innovations are much more likely to appear from unfamiliar sources such as newly formed firms and established firms diversifying from an unexpected quarter (Sosa, 2009). Challenges may also come from emerging fields of science or technology, and especially potent challenges from confluences of new fields (Maine, *et al.*, 2014). One may wish that the path ahead will be placid and free of surprises, but that is seldom the case. Change seems to occur in multiple waves often in quick succession after a period of stability.

New entrants look at competition as symbiotic and enter un-served or underserved niches, while incumbents view completion as a stable game of predator-prey or win-lose battles for share. Incumbents spend far too much incrementally defending the old or at best embracing hybrids of new and old far beyond the time that those investments make economic sense (Suarez, *et al.*, 2018). Venerable firms seem to resist new ideas and opportunities, and they seem consistently to underestimate the rate of technological change and adoption of new ideas (Foster, 1986). At the same time new entrants almost never seek to compete in the traditional product or service but consistently to champion new ideas. New entrants offer new technology or product architectures and expect rapid change (Christensen, 1997). Evidence seems pervasive in support of these points, and it is probably true of all sorts of organizations and decision not just confined to firms or products.

It seems only human to seek information that reinforces our values and experiences, and that if a threat that comes from innovation is presented as an existential challenge it may only be natural that it be resisted. Resistance would particularly ensue if no path for change seems available, in which case firms may resort to political means to defend themselves (Thompson, 1967).

The central problem then, as we see it is that new and rather hysterically termed “disruptive innovations,” often make the world better for established practice, at least for a substantial time, reinforcing conservative arguments that the new idea is no threat (Christiansen, Suarez and Utterback, 1998). Our research shows that, at least in the cases examined, a trajectory of competitive modes from symbiosis to zero-sum competition with predator-prey modes during the transition tends to be the dynamic norm. New practice usually begins in market niches not served or occupied, or even feasible for the established practice and may spread from there to direct confrontation in established niches. Well-established products may keep growing for a substantial time before declining and even continuing to prosper in some niches while the newer practice captures the premium growth in the market.

As mentioned above the advent of machine made ice in the 1860s dramatically expanded the demand for harvested ice cut and stored during the winter for summer use. Then manufactured ice was far more expensive than the natural product, and plant production capacities were miniscule compared to the massive amounts harvested (700,000 tons in Boston alone at the same time). Even so from less than a handful of plants in the 1860s, the number had grown to 30 in the southern states in the US and 5 in California by 1879 (Utterback, 1994, P 154). Manufactured ice simply filled a different niche in the market, provision of ice in hot southern climates, particularly those that were distant and that lacked water transport routes. Several of the earliest ice plants were built in Texas. Symbiosis followed, since alternate sources of ice made refrigerated meatpacking, food storage and transportation available year round everywhere even when the natural product was in short

supply. Natural ice was cheaper when available, but more expensive man-made ice could fill in when not. Ultimately the introduction of machine-made ice *tripled* the sales of harvested ice by making refrigeration dependable, year round and ubiquitous in every region and use.

With the invention of the transistor by Bell Laboratories in 1947, the press confidently announced the death of vacuum tubes. However, that did not happen for several decades. In fact the sales of tubes grew rapidly for at least fifteen years after the transistor entered the market. As with manufactured ice production processes were unreliable at first, volumes small and costs high. While the size and ruggedness of the transistor made it perfect for several new applications such as hearing aids and small portable radios, its low power and instability with rising temperature made it infeasible for many others (White, 1978). Many hybrid products combining tubes and transistors such as televisions that could turn on 'instantly' were developed, another example for a time of symbiosis. Today there are still some legacy applications dominated by vacuum tubes. Tubes have progressed from being a commodity to being valuable relics, as have mechanical watches and vinyl records and even ice for display at your local fish market or oyster bar.¹⁰ Distinguishing between a product-class and the underlying technology is important here.

Is the assumption then that all competitive races are zero-sum games, if I win you must lose, the reason for so many erroneous forecasts and missed investment decisions? Our socialization through competitive games and sports, in addition to selective perception of contrary evidence, might certainly cause us to make so many egregious errors of both excessive defense and postponed offense. We believe the root cause may well be that symbiosis may be the usual expectation at the beginning of competitive races. We expect the strengths of highly evolved practices to prevail and new ideas to fail when we are confronted by competitive threats. Surely no one saw that the pixilated black and white images produced by Sony's Mavica electronic digital still camera would compete with the beauty of silver halide images on film when it was introduced, and hugely expensive in August of 1981. As with our other examples though digital still photography filled an unoccupied niche in sports and news photography and relentlessly improved from there to become the pervasive success we see more than 40 years later, making ubiquitous the use of photography in the process.

Implications for Strategy

Early proponents of the idea that composite building panels would be an important new opportunity were dismissed. The industry's experience with the then available material, wafer board, was that it was inferior, of low value and performance, and good only for limited applications, for example in cheap cabinets and case goods. The idea that seemingly similar oriented strand board (OSB) made with the same seemingly waste materials, called 'weed wood' in the industry could be made into a stronger and stiffer product than plywood

¹⁰ It is important to note too that the replacement of an established technology in its dominant use does not necessarily spell death. As gas lighting replaced kerosene, kerosene found a large new market as motor fuel. As electric incandescent lighting replaced gas, gas found larger new markets for household cooking and heating.

and at much lower cost seemed unbelievable to management. At best it would be a minor specialty like wafer board.

The last confrontation in the industry's history was that between lumber and plywood. So suppose we look at that as a comparison rather than continue in a direct confrontation one asked. When early demand for plywood was compared with lumber, and then early sales of OSB was compared with plywood the slopes of the curves were remarkably similar! Moreover, when by adding a simple and inexpensive step to the wafer board production process (orienting the wafers in alternating layers) the inferior product could become the superior one.

When entry barriers are high, we should expect little or no entry and slow price changes, but in the reverse case, as in OSB, the opposite might be true, and that turned out to be the case. There was no need to build a whole new plant to try the idea at scale. Seeing analogous scenarios convinced management they must move ahead sharply with OSB. Early industry adopters became rare incumbent leaders in a new product line.

Over years new markets have opened for variants of OSB. Machinery developed to produce OSB compressed the layered material into 8 by 32 foot sheets. (The sheets are subsequently cut into 8 by 4 foot panels, the traditional dimensions of both sheathing panels and of pick up truck beds). Larger panels turn out to be perfect for applications such as floors for mobile homes and other pre-fabricated structures such as some roof components. Further experiments have created OSB in corrugated sheets and sheets with channels molded for utilities.

By relaxing the constraints imposed by limited amounts of high-quality raw materials, composite products have fueled the renaissance of wood-based building techniques and enabled an expansion of forest products use in construction extending remarkably even to high-rise buildings (Cornwall, 2016).

In this work we are not trying to develop forecasts, but rather consistent scenarios for change, given data on adoption of new products. Nor are we about understanding the behavioral and economic drivers of adoption beyond the degree to which they are incorporated in the aggregate data. We build on our previous work of more than twenty years and the theories developed then, by using data over five decades of one case and the rapidly advancing software tools to show that technologies may indeed interact in symbiotic, predator-prey and pure competition modes; and that the nature of their interaction will dynamically shift from one mode to another.

We suggest that these insights will find useful application in the development and execution of innovation strategies, and also lead to further research in this exciting field. Use of any model for strategy assumes it will be revisited periodically when new data become available, especially data about new product versions or technologies (Christiansen, Suarez and Utterback, 1998).

New Directions for Research

The model we have presented requires no simplifying assumptions. All variables and coefficients can be computed from primary data. Analysis of diffusion can be done not simply of one new product (N) contending with one established product (M), but rather for multiple M_i and N_j . We have shown that competitive modes are dynamic probably moving in most cases from symbiotic, through predator and prey modes and finally evolving into

pure competition, and finally that the coefficients of the competitive mode can be calculated directly as it evolves. The next logical step in this work is simulation of a competitive race among products using calculated dynamic c coefficients.

Another logical step is to examine a case for which a real product evolves into a virtual service. A case we have analyzed is the transition from real to virtual in recorded music, and that involves serious issues of metrics and units. Music has evolved from single songs recorded on a cylinder or both sides of a disc in Edison's day, to different record formats (72, 45 and then 33 1/3 rpm), to compact discs, and finally to subscriptions to music streaming services. What is the meaning of units when one can consume all the music possible in a month for a low monthly fee, and how can that be compared to an hour or two of music recorded on a record or compact disc (Yilmaz, 2017)?

How might we consider the measurement of a product or service when the very boundaries of a product are constantly variable? What shall we consider the product or service definition or the units of measure to be when a cell phone evolves to become multi-purpose remote device with hundreds of functions embedded in it? This is truly a difficult conundrum to resolve!

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