THE DYNAMICS OF INNOVATIVE INDUSTRIES

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ABSTRACT

This work captures and analyzes the fundamental dynamics of innovative industries with a System Dynamics model. We selectively reviewed the innovation literature, identified the dynamics to be modelled, formulated a conceptual model of these dynamics, and then developed the initial simulation model. By design the conceptual model is simple and generic. It is intended to apply to a broad range of products and services – assembled and process-based, complex and simple, physical and digital, business and consumer, early stage and mature, 19^{th} century and 21^{st} century. That is what we mean by the "fundamental dynamics" of innovative industries. In many variations and combinations they can explain the evolution of most markets. The initial simulation model was developed from the conceptual model. It represents products based on two generations of technology. At this stage the simulation model does not represent a specific market or industry. It is quantified with hypothetical inputs, parameters, and cause/effect relationships. The simulation model recreates well-documented reference modes of market evolution. We currently are building the information base which will enable the initial model to be applied to the photography and display markets.

Introduction

This work builds on an extensive body of research and publications. Its roots lie in the work of Abernathy and his collaboration with Utterback[1]. Over the ensuing years a rich collection of empirical studies, conceptual frameworks, and quantitative models of innovation were developed. Key contributors included Afuah, Christensen, Henderson, Klepper, Roberts, Sull, Suarez, Tushman, and Utterback.[2]

Our objective is to capture and analyze the fundamental dynamics of innovative industries with a System Dynamics model. We selectively reviewed the innovation literature, identified the dynamics to be modelled, formulated a conceptual model of these dynamics, and then developed the initial simulation model. At this stage the simulation model does not represent a specific market or industry. It is quantified with hypothetical inputs, parameters, and cause/effect relationships. The simulation results approximate many actual cases. We currently are building the information base which will enable the initial simulation model to be applied to the photography and display markets.

The Dynamics of Innovation

The literature highlights dynamics which are fundamental to the sources of innovations and their impacts on firms, markets, and industries. These dynamics include:

- Entry and exit of firms;
- Experimentation and innovation;
- Technology evolution;
- Improvements in cost and performance;
- Emergence of standards and dominant designs;
- Adoption of new technology;
- Network effects;
- Development of a mass market;

[1] See Abernathy (1978), Abernathy and Clark (1985), and Abernathy and Utterback (1978).
[2] Selected references to their publications can be found at the end of this paper.

- Market growth;
- Market saturation;
- Intensity of competition; and
- Commoditization.

The entry of firms into a market and the subsequent exit of many or most competitors are central to the dynamics of innovation.[3] In the early stage of a new market or generation of technology the perceived opportunity is large. No firm is dominant. The product or service is not highly refined and there are many competing variations. As the number of companies in the market grows so does the rate of experimentation and innovation. The market is in a very fluid state where both suppliers and customers must contend with substantial uncertainties.

In the early stage of market development standards usually are rudimentary or unclear. Competing standards create risks for both suppliers and customers. At some point the dominant standards, design, and form factors emerge. These often are not the "best" from a technical performance or user perspective. But the tipping dynamics are very powerful once they get going.

At this point the game changes dramatically. The focus shits from experimentation and product or service innovation to refinement of the dominant design and the pursuit of efficiency and quality. Product innovation becomes incremental. Process innovation leads to large-scale, highly specialized facilities. In most markets only a small number of firms survive the transition. The others exit the market or are absorbed in one or more rounds of industry consolidation.

Costs decline and performance improves rapidly following the emergence of the dominant standards and design. The few surviving firms offer very similar products or services. Competition grows increasingly intense. Certainty about standards, greater availability of information, building network effects, declining prices, and improved performance accelerate the development of a mass market.

As the market matures the product or service is "commoditized." This term denotes a competitive environment in which product differentiation is difficult, customer loyalty and brand values are low, competition is based primarily on price, and sustainable advantage comes from cost leadership.[4] Commoditization is driven by excess capacity. There are recurring cycles in investment, capacity utilization, prices, and profitability. In commoditized markets intense competition de-couples prices from costs, margins are highly sensitive to capacity utilization, innovation slows or stops, and the sources of sustainable advantage are less tangible.

[3] These dynamics are described in Utterback (1994).
[4] See Weil (1996) and Weil and Stoughton (1998) for a description of research into the dynamics of commoditization.

The preceding dynamics describe one phase in the evolution of a market. But most markets experience periodic waves of innovation. For some time two or even three generations of technology co-exist. The interactions among these generations are quite complex and have major impacts on the longer-term dynamics of innovative industries.

Competition between generations of technology is affected by both objective and emotional factors. Relative price and performance have a significant impact, particularly if the new generation of products or services better meets new needs or values of customers. Network effects can be quite powerful, where the value increases non-linearly as a function of the number of users. But fear and fashion also are important. Risk averse customers are hesitant to adopt a new and "unproven" technology. Will the performance be as promised? Will this become the dominant standard? Will my boss approve? Will my friends think it's cool?

When disruptive innovation enables a new generation of products or services the dominant companies in the market often are complacent and slow to react.[5] They seem unconcerned, uninterested or even dismissive. The new technology may be considered "inferior" or "a niche market." It does not fit with the paradigm of the dominant companies and does not appear to be a sufficiently large opportunity.

While the established companies may participate in the new technology they usually focus most of their resources and attention on the older generation. Indeed, as they feel more and more pressure from the new generation the incumbents often find ways to substantially refresh the old technology, boosting its performance to much higher level. But typically they struggle to be successful with the new technology. Innovation obsoletes important aspects of the incumbents' capabilities and knowledge, which tend to become deeply embedded in their structure and processes.[6] The most frequent outcome is a change in market leadership.

A Conceptual Model

The dynamics of innovation are interrelated. The causal loop diagrams in Figures 1 and 2 highlight the key linkages. Figure 1 centers on the number of firms in the market. The entry rate is determined by the expected growth and profitability of the market and availability of finance. In the early fluid stage of a new generation of technology the size of the prize is quite uncertain. Thus a "lemming effect" often occurs, where the inflow of entrants reinforces the impression that this must be the "new big thing," attracts a large amount of investment, and thus encourages additional firms to enter the market. In a relatively short time there can be a surprisingly large number of companies in the market. These self-reinforcing dynamics were conspicuous during the dotcom boom.

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[5] This is the behavior of incumbents described in Sull (1999) and Christensen and Overdorf (2000).
[6] See Cooper and Schendel (1976), Utterback and Kim (1986), Henderson and Clark (1990), and Utterback and Suarez (1993).

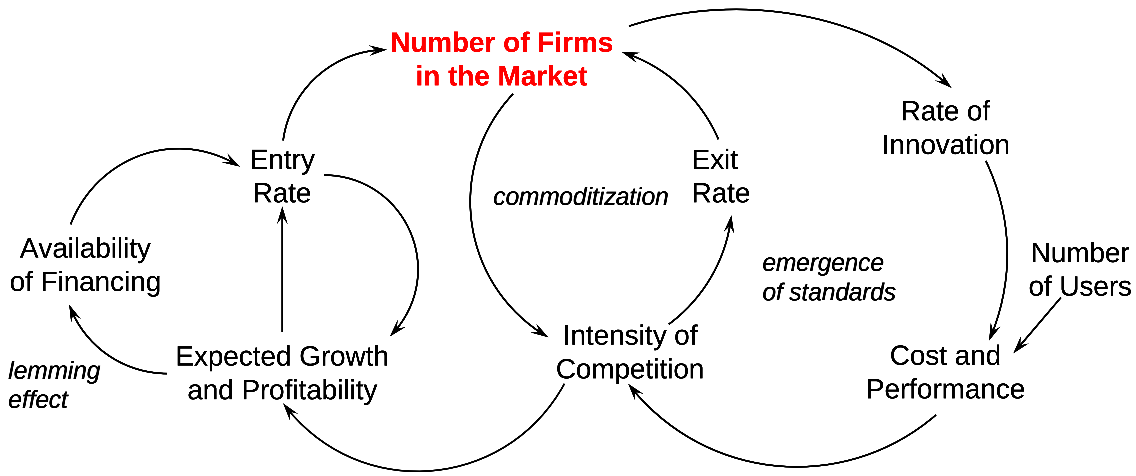

Figure 1: Number of Firms in the Market

The large number of firms generates a high rate of experimentation and innovation. This is the hallmark of the fluid phase. Continual innovation and the increasing number of users of a new technology drive improvements in cost and performance. But the diversity of designs and standards creates significant uncertainty. The need for standardization grows. Then the dominant standards, design, and form factors emerge.

As the market becomes more crowded and standards emerge, the intensity of competition increases and the products or services commoditize. This has two reinforcing effects on the number of firms. First, the entry rate slows because potential entrants reassess the attractiveness of the opportunity. Second, a growing number of firms exit the market. Some companies give up in frustration. They have failed to achieve performance targets, e.g., for sales and profitability. Others go bankrupt or are acquired. The number of firms in the market peaks and declines. The rate of innovation slows and shifts from product to process.

They dynamics of technology adoption are captured in Figure 2. The adoption rate of products or services based on a new technology depends on both the number of potential users and their willingness to adopt. As discussed above customers' willingness to adopt a new technology depends on both objective and emotional factors, i.e., price/performance, network effects, and perceived risks

Unit cost generally declines and quality improves as a function of cumulative production. This is the so-called "learning curve" effect. Emergence of the dominant standards and design triggers industry consolidation, leading to a few large suppliers. They can realize substantial economies of scale, contingent of high levels of capacity utilization. During this transition phase incremental innovations continue to improve performance while process innovations improve productivity and quality. The emergence of standards also enable network effects.

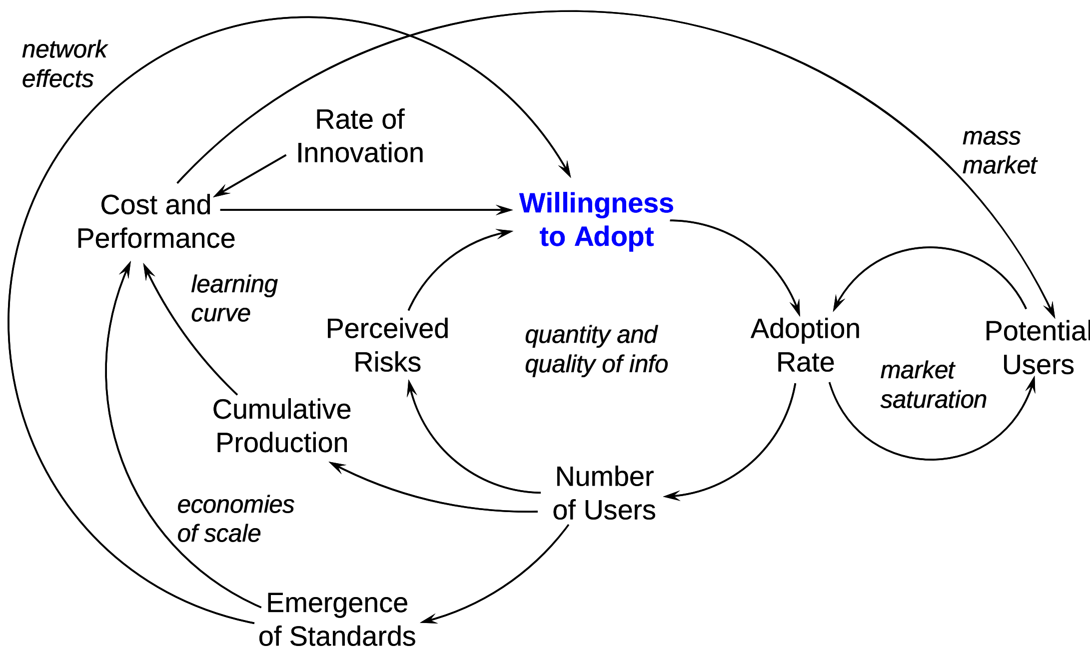

Figure 2: Willingness to Adopt New Technology

The perceived risks of a new technology can be high in the early stage. It is unproven, and potential users have reason to be skeptical and cautious. Things start to change as the number of users increases. The quantity and quality of information about the new technology improves, allowing more confident assessments and decisions. Highly respected "reference users" legitimize a new technology and make its selection much easier to defend. And products or services based on the new technology can become a fashionable "must have." This happens in business markets as well as consumer markets, e.g., the rush by companies in the late 1990s to get on-line. Then the risk is of ***not*** adopting, of being seen as "behind the times" or "not getting it."

The key ideas and linkages in Figures 1 and 2 were integrated in the simple conceptual model presented in Figure 3. This model connects the number of companies in the market, technology evolution, adoption of new technology, and the profitability of the companies. The other fundamental dynamics of innovation are represented, i.e., entry and exit of firms, improvements in cost and performance, market growth, intensity of competition, and commoditization.

By design the conceptual model is simple and generic. It is intended to apply to a broad range of products and services – assembled and process-based, complex and simple, physical and digital, business and consumer, early stage and mature, 19th century and 21st century. That is what we mean by the "fundamental dynamics" of innovative industries. In many variations and combinations they can explain the evolution of most markets.

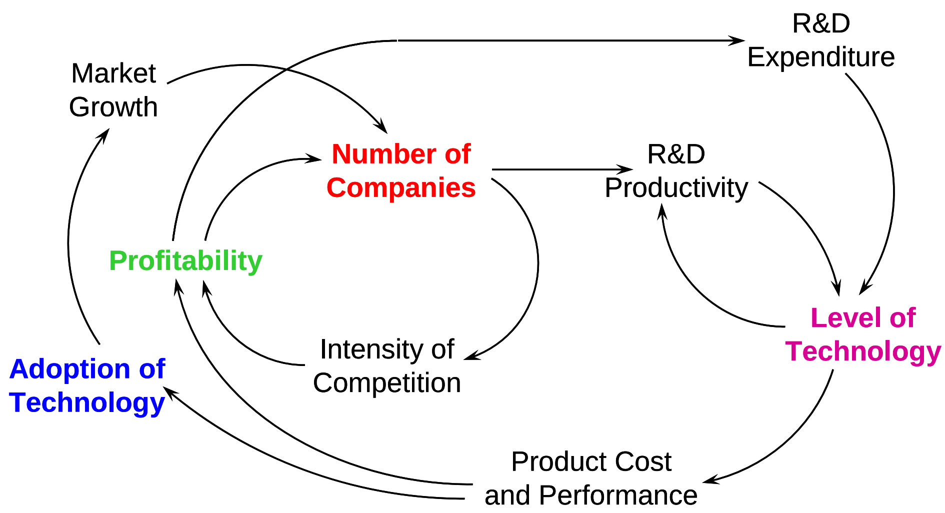

Figure 3: Integrated Conceptual Model

The Simulation Model

The initial System Dynamics simulation model was developed from the conceptual model in Figure 3. It represents products based on two generations of technology, subscripted [old] and [new]. Simulations run from 1990 to 2020. The new technology is launched in 1998. At this stage the simulation model does not represent a specific market or industry. It is quantified with hypothetical inputs, parameters, and cause/effect relationships. The principal market-defining inputs are listed in Figure 4. In very approximate terms they could describe the US market for wireless appliances.

initial companies [old]	5
initial units in use [old]	10 million
normal retirement age [old]	5 years
base market growth	5-15% pa (cyclical)
initial price [old]	$500
initial margin [old]	17.5%
fraction of revenues to R&D [old]	4%
time to develop technology [old]	2 years

Figure 4: Market-Defining Model Inputs

Figures 5 through 9 show important segments of the model's structure, starting with the number of companies in the market. A complete listing is in Appendix A.

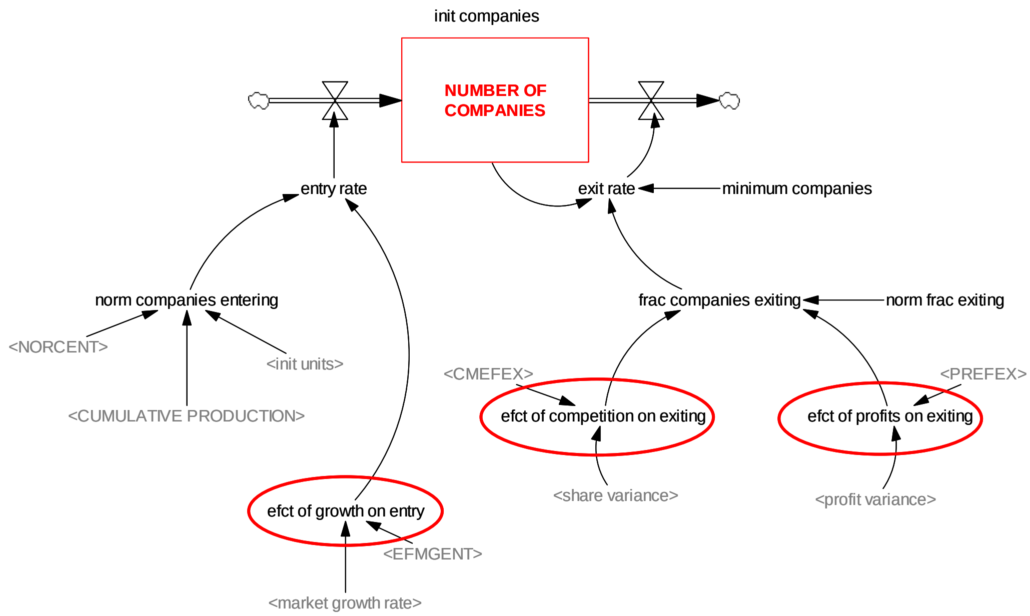

Figure 5: Number of Companies in the Market

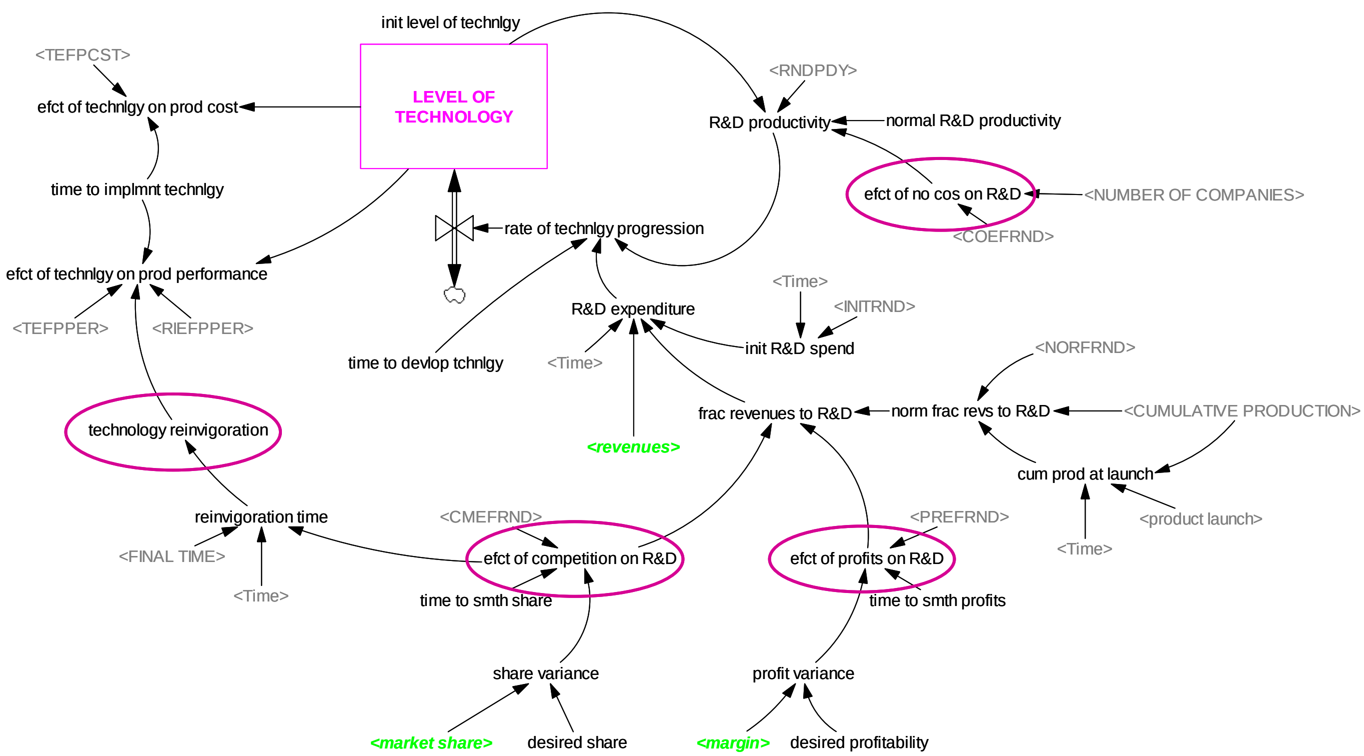

Figure 6: Level of Technology

Most of the variables and parameters in Figures 5-9 are subscripted [old] and [new]. The number of companies in the market offering the [old] and [new] products is determined by the entry and exit rates. Market growth affects the entry rate through a non-linear lookup function. The fraction of companies exiting is affected by both competition and profitability. Failure to achieve market share and/or profit objectives accelerates the exit rate.

The level of technology is an index defined as 1.0 in 1990 for the [old] technology. The rate of technology progression is determined by R&D expenditure and R&D productivity. The latter is the amount of expenditure required to progress the technology index by a fixed amount. The model assumes diminishing returns as a generation of technology matures. However a large number of companies in the market boosts R&D productivity because of their higher rate of experimentation and innovation. This effect is significant during the early fluid stage of market development. The computation of R&D productivity and key lookups are presented in Figure 7.

R&D productivity = normal productivity*effect of level of technology *effect of number of companies

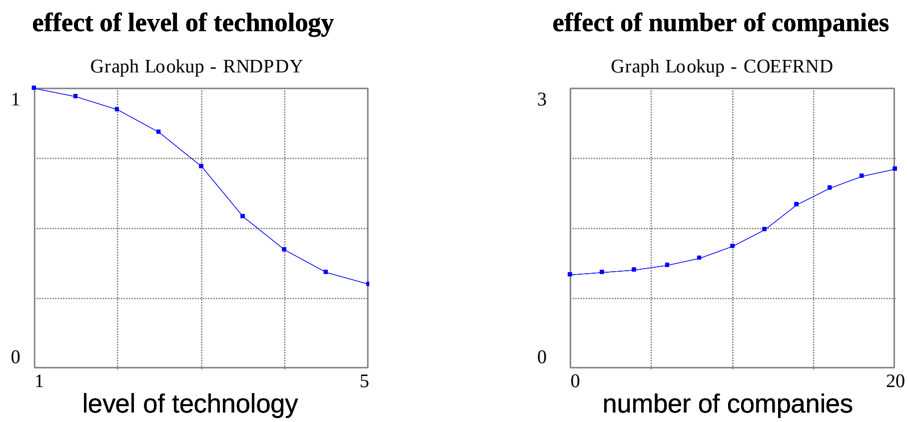

Figure 7: R&D Productivity

There are other noteworthy aspects of Figure 6. R&D expenditure is affected by both market share and profit performance. Failure to achieve market share objectives increases the fraction of revenues to R&D in an attempt to improve competitiveness. Not surprisingly, failure to achieve target profitability leads to a cut in R&D expenditure. Moreover when the [old] technology loses substantial market share, there is a major push to reinvigorate the technology and substantially increase product performance. This gives the [old] technology a reprieve and significantly extends its life.

The number of units in use of products based on the [old] and [new] technologies is determined by the sales and retirement rates. As shown in Figure 8 unit sales of the two generations of products depend on potential sales (from market growth plus the replacement of retired units) and the fraction to each generation. Retirements of the [old] products will be accelerated if price/performance of the [new] is significantly superior.

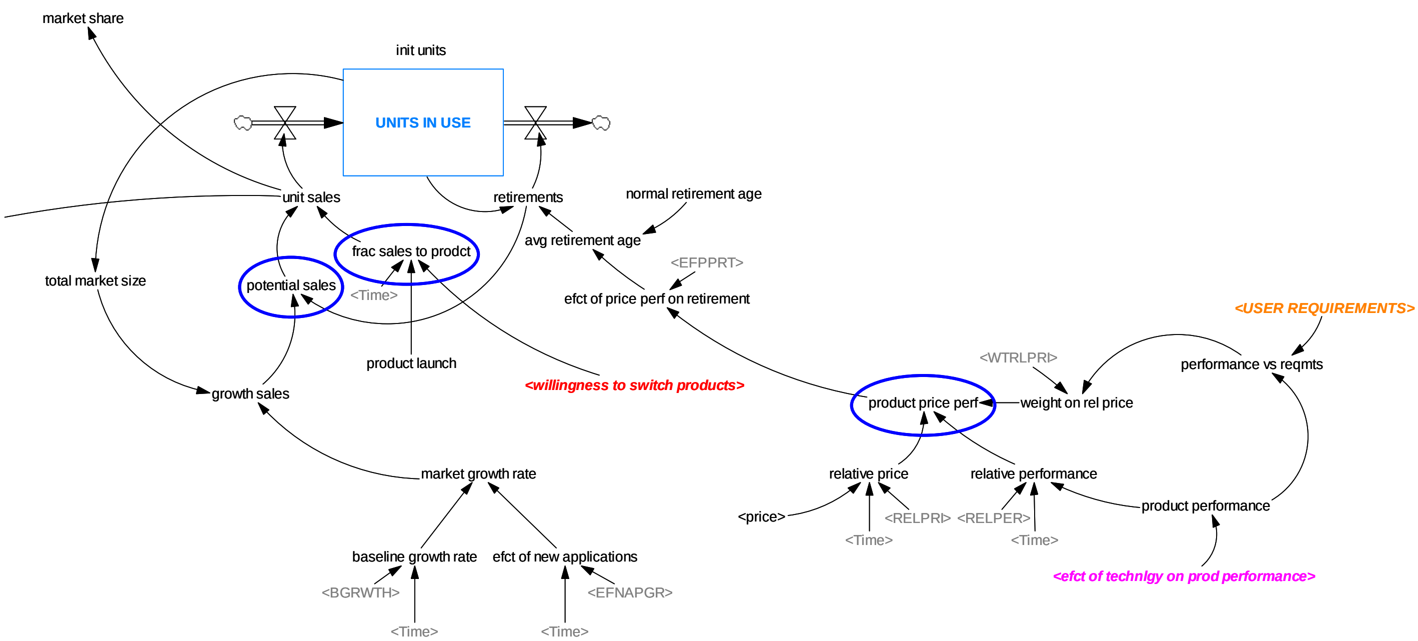

Figure 8: Product Units in Use

The fraction of sales to products based on the [new] technology is determined by users' willingness to switch. As discussed above this depends on a combination of objective and emotional factors. In the initial simulation model, willingness to switch to the [new] generation of products is a function of:

- The normal risk aversion of users;
- Relative price/performance;
- Size of the installed base of [new] products;
- User requirements; and
- Existence of standards.

The normal risk aversion describes users' appetite for risk. A small value, e.g., 0.05 denotes a highly risk averse market. The computation of willingness to switch and key lookups are presented in Figure 9.

fraction of sales to product [new] = willingness to switch products
willingness to switch products = normal risk aversion*effect of price-performance *effect of installed base*effect of user requirements*effect of standards
normal risk aversion = 0.15

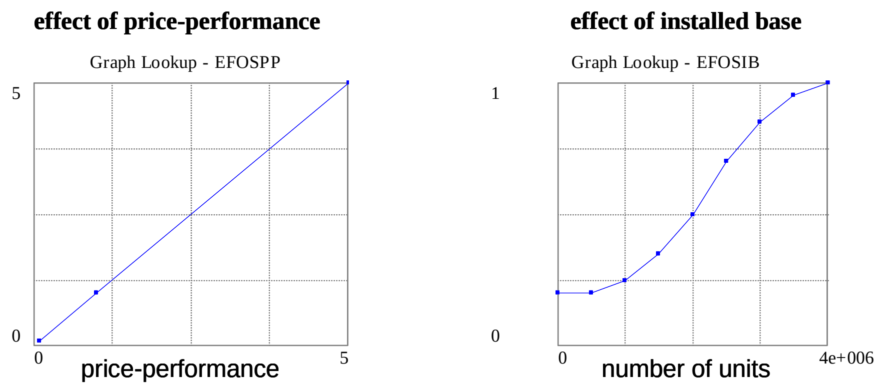

Figure 9: Willingness to Switch to the New Products

Simulation results from the initial model approximate many of the cases described in the referenced literature. Examples of the outputs are shown in Figures 10 through 14.

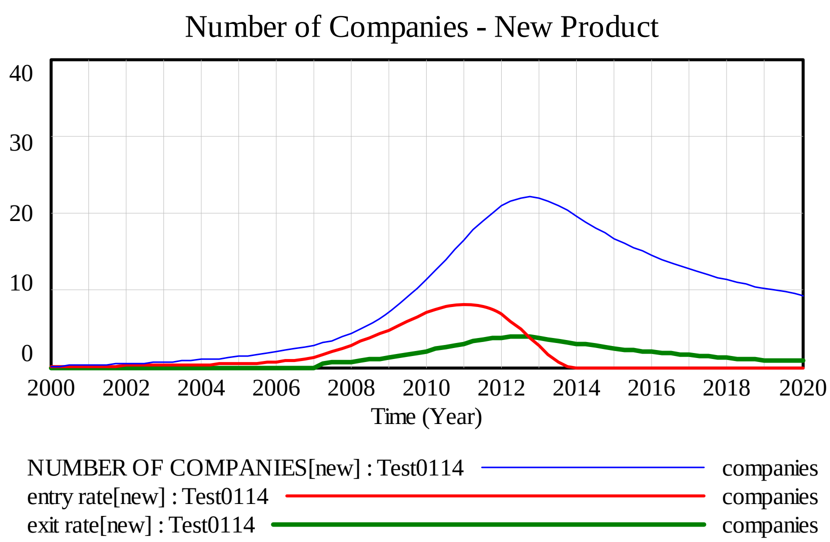

Figure 10: Number of Companies Offering the New Products

Please recall that products based on the [new] technology are launched in 1998. The number of companies offering the [new] products peaks in 2012, i.e., fourteen years later, at 22 and then declines to 9 over the subsequent eight years.

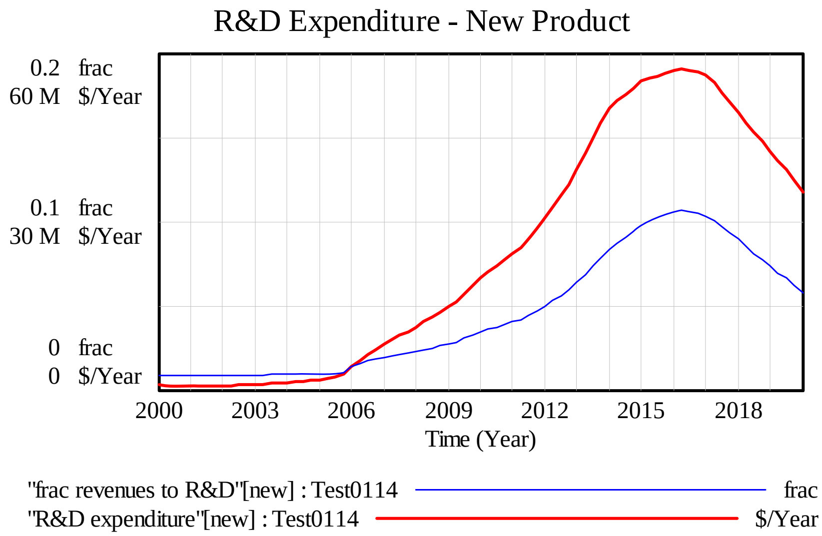

Figure 11: R&D Expenditure on the New Products

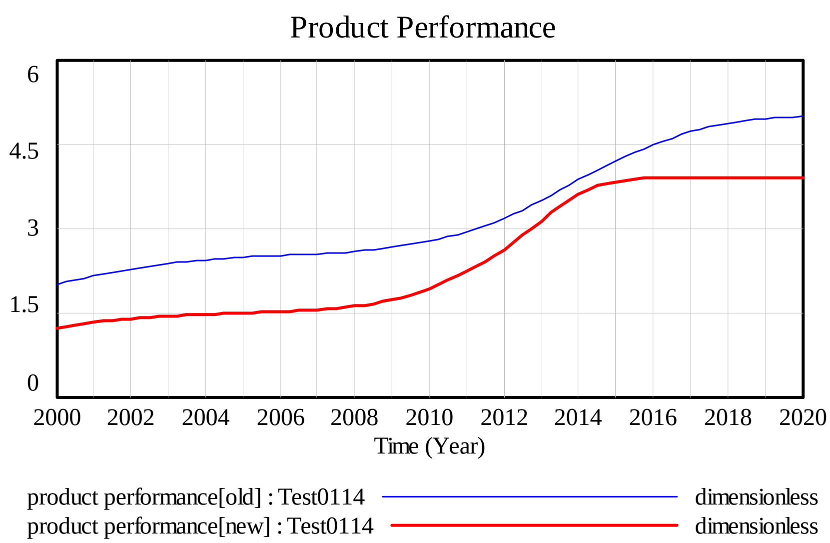

Figure 12: Product Performance

R&D expenditure on the [new] generation of produces starts out very low. The enabling technology for the early products already exists, e.g., it is brought by entrepreneurs to a start-up company or an established company applies technology it was using in some other market. Both the fraction of revenues to R&D and R&D expenditure grow steadily as the [new] product gains traction in the market. The bulk of the expenditure occurs between 2012 and 2020, as the number of companies declines.

The peak in the number of companies marks the transition from the early fluid phase of the market. The surviving companies spend a significant fraction of their revenues on incremental product improvements and process innovations to reduce costs.

The effect of these expenditures can be seen in Figure 12. Performance of the [new] products initially is well below the [old] products, and improves significantly during 2009-15. The performance gap between the two generations of products narrows. Indeed, performance of the [new] products in 2012 exceeds the performance of the [old] products in 2008. But the [old] products have been reinvigorated. As they feel more and more pressure from the [new] generation the incumbents find ways to substantially refresh the [old] technology, boosting its performance to much higher level. Thus the technology trajectory is not a simple "S-curve" but more like a "double-S."

The price of the [new] products also starts below the [old] generation.[7] Competition between the two generations causes most of the benefit of declining costs to accrue to users through lower prices. Companies offering the [new] products price increasingly aggressively in order to build market share. By 2016, i.e., eighteen years after their launch, the [new] products are completely commoditized.

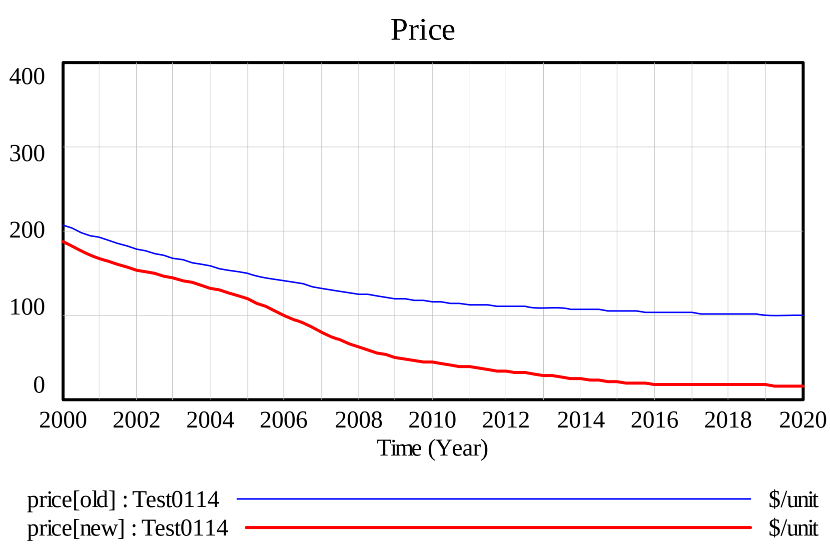

Figure 13: Product Prices

Despite very aggressive pricing adoption of products based on the [new] technology proceeds slowly. As one can see in Figure 14 they constitute about 1/3 of the installed base in 2020. The continued dominance of [old] products is consistent with many actual cases.

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[7] This combination of lower performance by traditional standards and lower price is consistent with the "attack from below" scenario described in Christensen (1997).

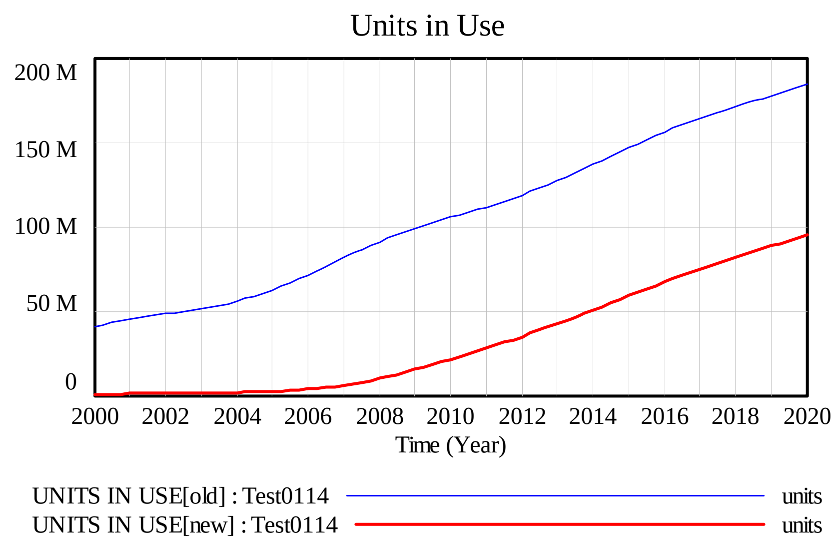

Figure 14: Product Units in Use

Next Steps

Our work to date has produced very promising results. The conceptual model provides a concise expression of the fundamental dynamics of innovative industries. The initial simulation model recreates well-documented reference modes of market evolution.

Results from the initial model raise many important questions:

- How do the decisions of established firms and start-ups differ?
- Why are the dynamics in the US different from Japan and Europe?
- What roles do social and other contextual factors play?
- Are the dynamics different for services?
- What if the innovation is a complement rather than a substitute?
- Which factors are most important in the emergence of dominant standards and designs?
- Why do these dynamics happen at different speeds in various industries?

- Do some innovations de-commoditize?

We currently are building the information base which will enable the initial simulation model to be applied to the photography and display markets. The next step will be to refine the model and use it to address some of the questions listed above.

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