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Technological Forecasting & Social Change
71 (2004) 67–80

Technological Forecasting and Social Change

Technology roadmaps: Infrastructure for innovation

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Received 20 August 2003; accepted 6 October 2003

Abstract

The value of technology roadmaps for technology planning, technology selection, and technological innovation has become widely recognized. In this article, we explore how technology roadmaps can support virtual innovation and innovation factories. We also consider how technology landscapes can provide metrics for technology roadmaps. We explore how knowledge of patterns of technological evolution can be incorporated into technology roadmaps to detect opportunities for innovation and possible market limitations. Finally, we discuss how agent models can provide the basis for simulation and possibly for self-organization.

Keywords: Technology roadmaps; Technological innovation; Virtual innovation

1. Introduction

Technology roadmaps are gaining in popularity as tools for managing the future of technology. A recent survey of the state of technology roadmapping reveals retrospective roadmaps to discover what past technologies, products, or organizations made a particular product or technology successful, the more familiar prospective roadmaps that marshal past and current technologies and products to argue for trends and likely successors, technology roadmaps to formulate strategy and to solicit and justify funding, and roadmaps to forecast technology and product changes [1,2]. Technology roadmaps have been developed with

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0040-1625/$ – see front matter
doi:10.1016/j.techfore.2003.10.002

vastly differing levels of specificity and for vastly different audiences. They have been characterized as both forecasts of what is possible or likely to happen and plans that articulate a course of action [3]. In contrast, Robert Galvin, the former CEO of Motorola and an early proponent of technology roadmaps, saw them as an "extended look at the future of a chosen field of inquiry composed from the collective knowledge and imagination of the brightest drivers of change in that field." To Galvin, they were primarily tools for innovation, representing "the inventory of possibilities for a particular field" [4].

At present, technology roadmaps are hard-pressed to capture that inventory of possibilities. They are often PowerPoint or Visio drawings that are difficult to manipulate and maintain. In fact, the difficulty of maintaining technology roadmaps is often cited as a major obstacle to their effective use [2]. Collaboration, especially remote collaboration, is equally difficult. Perhaps not surprisingly, those involved in consulting often tout the value of the process of creating technology roadmaps for discovery and consensus building, while downplaying the value of the final product. Using roadmaps for innovation, however, emphasizes the value of the roadmaps themselves. Such roadmaps require more than ad hoc construction.

In this article, I will argue that delivering the underpinnings of persistence, manipulation, and collaboration will not only solve the manipulation, maintainability, and collaboration problems of technology roadmaps, but will provide the basis for extending the value of technology roadmaps in important ways. Specifically, I will argue that technology roadmaps can become important drivers of innovation, provide convergence between innovation and forecasting, can represent the coevolution of technology and markets, and because they reflect an evolutionary organization of technology, can contribute to their own self-organization.

2. Functions of technology roadmaps

The principal functions of technology roadmaps have been for representation, communication, planning, and coordination and, to a degree, for technology forecasting and selection. Technology roadmaps typically provide a time-directed representation of relationships between technologies and products. That core set of relationships is often augmented with connections to markets and on occasion to the organizations involved in delivering the technologies and products (see Fig. 1). One of the best-known and most-often referenced technology roadmaps, the semiconductor roadmap maintained by Sematech, communicates and coordinates the efforts of the members of the consortium. Much smaller roadmaps serve to coordinate the efforts of departments within a single company and to align their efforts with the overall objectives of the firm.

Elsewhere [5], I have suggested a partial catalog of enablers of capable roadmaps. Most importantly, roadmap elements, their attributes, and relationships must be persisted—all other aspects of roadmap construction presuppose it. To "persist" technology roadmap elements or entire roadmaps is to give them permanence by providing persistence to the (software) objects that represent the roadmap or its elements. Specifically in object technology, "to persist" objects means to invoke the persistence mechanism of the particular object implementation in order to preserve or store the identity and state of objects, typically in a database. Without

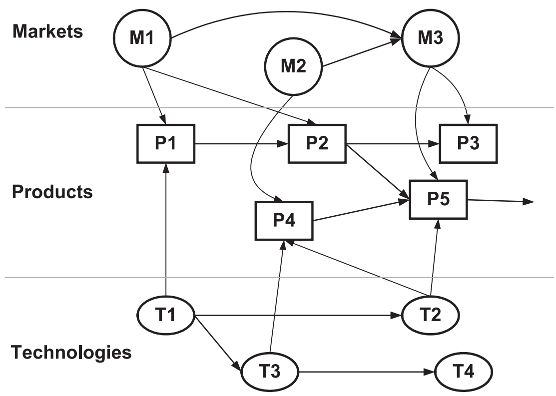

Fig. 1. Generic technology roadmap.

persistence of roadmap elements, any technologies and products that are envisioned, but not developed, cannot influence further envisioning. As roadmaps grow in size and scope, they require user interfaces for manipulation and collaboration. Finally, just as several users may have to collaborate on a single roadmap, one or more users may want to integrate several roadmaps. Roadmap integration facilitates bringing elements from different roadmaps together to widen the context of innovation by drawing in otherwise unrelated technologies.

When technology roadmaps are implemented through object technology, their product, technology, market, and other nodes would be modeled as software objects. They would represent their roadmap and real-world counterparts by storing their attributes as well as maps of their relationships with other roadmap elements. The objects' methods or behaviors, essentially small programs stored inside the objects, would perform a variety of functions from housekeeping to searching the roadmap for related objects (products, technologies, markets) whenever new objects enter the roadmap. In that manner, the objects could be made responsible for maintaining their own relationships. If they are enabled to act independently, these objects could be viewed as software agents and the resulting model would become an agent model.

Implementing technology roadmaps through object technology addresses many of their key requirements. Object technology automatically provides persistence, solving the headache of maintaining technology roadmaps. It enables manipulation and collaboration. It also creates the foundation for integration, for incorporating metrics, and for self-organization.

3. Technology roadmaps as drivers of innovation

Even the simplest technology roadmaps naturally encourage one to envision what might be next in line. If P3 and P5 in Fig. 1 represented recent generations of PDAs and notebooks, one can almost picture a new hybrid, the tablet computer, which reached the market late in 2002. The value of these roadmaps for innovation lies in their suggestiveness of new technologies and products based on the evolution and juxtaposition of existing technologies and products. Innovating beyond the next generation requires virtual innovation; using technology roadmaps to innovate systematically calls for innovation factories.

4. Virtual innovation

Virtual innovation seeks to innovate without creating tangible prototypes and products. Traditional innovation proceeded from conception to prototyping to manufacturing. Since prototypes frequently were costly to create, and since requirements and specifications drove prototypes, getting to the prototype stage implied a serious commitment to produce a product. Increasingly, physical prototypes are giving way to models and simulation. In a complete role reversal, these virtual prototypes now drive the requirements and specifications for production products. This growing emphasis on virtualization is fueling a desire to virtualize innovation itself [6]. The dizzying pace of innovation can continue uninterrupted by the challenges of implementing the technology in a physical prototype, let alone a full-fledged product. Technology roadmaps are critical for virtual innovation because they provide a mechanism for persisting, and thereby giving permanence to, individual virtual innovations. Both products P6 and P7 in Fig. 2 constitute virtual innovations, but it may not be possible to envision P7 based on P3 and P5 alone. Without somehow giving P6 a representation on the technology roadmap, P7 may not be conceivable, or would at any rate be a different product.

Consider the example of Sony's Pen-Tablet desktop. It featured a touch screen that could be held on ones lap for drawing and entering data with a stylus. The touch screen, however, remained tethered to the chassis. Although Sony chose to produce the unit, one can imagine circumstances that would make this hybrid uncertain of a market. In fact, Sony abandoned the VAIO Pen-Tablet line after only one year, in spite of a third generation in the pipeline, due to sluggish sales. In the past, shelving a product idea would often make it vanish altogether. Keeping the idea of the Pen-Tablet around as a virtual, but never realized technology or product (P6), might just have speeded up the development of the tablet PC (P7), which appears to enjoy a definite market. To exert forward influence, virtual innovations must leave

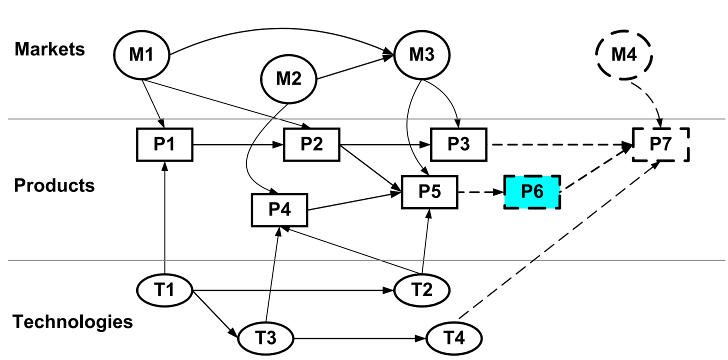

Fig. 2. Virtual innovation.

a marker on a technology roadmap, with a name and list of attributes, to provide a stepping stone for future innovations.

5. Innovation factories

The heyday of the technology bubble during the late 1990s saw a resurgence of interest in systematic innovation. Epitomized by companies like IDEO and IdeaLab, innovation factories sought to become knowledge brokers and innovators by creating the right environment for innovation. That environment had to be conducive to capturing good ideas, keeping ideas alive, imagining new uses for old ideas, and putting promising concepts to the test [7]. What better way to capture ideas and keep them alive than place them on a technology roadmap? The trouble is that the good ideas that prove of value to a product on one technology roadmap all too often languish in side branches of other technology roadmaps. This is the challenge of what has been called architectural innovation [8], where new innovations come about as the result of rearranging existing components. As the experience of TRIZ,[1] which sought to systematize innovation based on a study of patents, has shown, most useful ideas for innovation based on a particular technology lie outside the area of expertise reflected in that technology.

Ideas that are kept alive can become effective either actively by finding their way onto all the right roadmaps or passively by being found through searches. For the results of virtual innovation and other older innovations to exert their influence on downstream or lateral innovations, they must find their way onto a roadmap. The challenge is that the appropriate real or virtual innovations must somehow find their way onto every relevant roadmap. The other mechanism of technology roadmap integration involves searching for potentially relevant technologies. Whether technology roadmap nodes advertise their relevance or are discovered through searches, they can yield new innovation through integration with other nodes (Fig. 3). Technology roadmaps implemented with object technology would naturally provide the capability for roadmap integration. As the sweep for possibly useful technologies and products widens, it becomes ever more apparent that technology roadmaps become large and must be automated.

An example of roadmap integration is VMWare, a virtual machine technology. It applies ideas and technologies developed for IBM mainframes in the 1970s, and sold as the VM operating system, to a new generation of hardware and software. As Intel servers had become more powerful and at the same time less utilized, someone realized that running more than one operating system on a particular server would improve its return on equity. Having the experience with VM to look back to eliminate the need to reinvent this solution. The challenge of keeping ideas alive is further illustrated by Boeing's proposed blended wing body design for future civilian aircraft (Fig. 4c)[2]. It marks a radical departure from the

[1] See the *TRIZ Journal* at http://www.triz-journal.com.

[2] Picture Sources: (a) Lockheed Flying Wing concept: Aircraft Design (http://www.aircraftdesign.com), (b) Douglas DC-3: Museum of Flight (http://www.museumofflight.org), and (c) Blended Wing Body: NASA Glenn Research Center (http://www-psao.grc.nasa.gov).

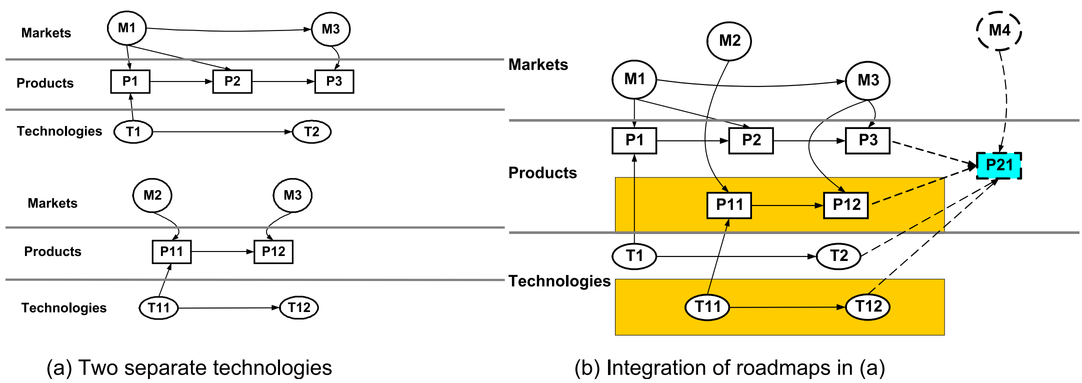

Fig. 3. Innovation factory: technology and product integration. (a) Two separate technologies. (b) Integration of roadmaps in (a).

conventional tube-and-wing design exemplified by the DC-3 (Fig. 4b). If the blended wing body truly represents Boeing's vision of the future, one must wonder whether the right roadmap could not have allowed the Lockheed flying wing concept of 1938 (Fig. 4a) to challenge every new generation of tube-and-wing design, from the DC-3 that entered service in the mid-1930s to the 777 and the recently proposed 7E7.

The ultimate innovation factory would take the form of seamlessly linked roadmaps that connect to all the other roadmaps. Because it would provide the broadest possible context for innovation, it would be particularly useful for searching for new disruptive technologies, which are notoriously difficult to ferret out.

It may be tempting to think that at least historically there is a single master technology roadmap just as there is but a single evolutionary tree. At least with respect to technology, that would ignore the social and individual perspectives of technological change. As Linstone has demonstrated [9], the technical, social, and individual perspectives cannot be reduced to each other. In the case of VMWare, it is entirely conceivable that the creators of VMWare reinvented virtual machine technology and only later became aware of its precursor in IBM's VM operating system. In that case, rather than simply calling one the logical precursor, it would be far more profitable to investigate what triggered someone to reinvent the solution.

Fig. 4. Innovation factory: keeping ideas alive.

6. Convergence of innovation and forecasting

In a retrospective on the 30th anniversary of *Technological Forecasting and Social Change*, Linstone [10] noted not only a decline in research and publications on technology forecasting, but a shift away from traditional forecasting methods toward, among others, roadmapping. In light of the foregoing discussion about virtual innovation, this should not come as a surprise. As virtual innovation adds new elements to a roadmap, these new virtual artifacts take on the same role as virtual observations or projections in traditional technology forecasts. In the process, they fill in the future elements of the inventory of possibilities of a particular field.

If we can create virtually today what would otherwise become real artifacts in the future, we do not have to forecast them. In that respect, innovation and forecasting are converging. Virtual innovation provides new points for a forecast, while innovation factories broaden the context by seeking to draw all relevant data points into the forecast. Forecasting in the traditional sense continues to be useful for timing of when virtual innovations might be turned into real products and for other temporal relationships on a technology roadmap.

7. Technology landscapes: developing metrics for roadmaps

Technology roadmaps provide a map of the unfolding evolution of technologies and the products that implement them. They lack, however, any indication of the value of individual nodes or entire paths through the roadmap. What both technology providers and consumers need is a metric for their technology roadmaps.

The technology landscapes introduced by researchers at the Santa Fe Institute constitute a particularly useful metric [11]. These landscapes combine measures of the closeness or relatedness of technologies, represented primarily by the roadmap, with measures of the value of a technology to the technology developer or consumer. The height of the landscape provides a measure of its profitability or its value. That value could be the size of the market, the creative potential of a technology, the ease of switching, or the value of alternative products or technologies, individually or on a specific path through the roadmap and the landscape.

Consider the technology roadmap and its associated technology landscape shown in Fig. 5. The value of technology T2, as measured by the height of hill A is simply not as attractive as either technologies T3 or T4, represented by hills B and C. However, and this is crucial, the technology sequence T1–T2 is separated by a deep valley from technologies T3 and T4 (B and C). This ruggedness in the landscape indicates a considerable cost of switching from T1–T2 to T3–T4. It would provide a measure of the risk to the consumer of switching product lines as well as the potential cost to the technology provider of switching core competencies. Landscapes with peaks separated by deep ravines imply great opportunity if consumers choose the peaks associated with a company's products and equally great risk because of the cost these consumers would

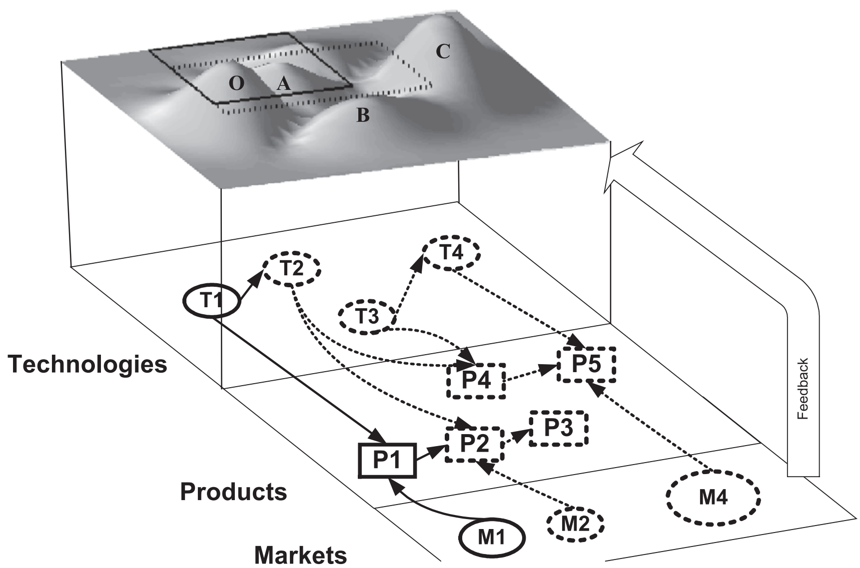

Fig. 5. Technology landscape as metric for technology roadmap.

incur in switching from one product to another. Standardization smoothes the landscape and would reduce risk, but usually at the price of lower profitability of individual products and technologies.

These landscapes capture another critical aspect of technology selection. Instead of pretending to a bird's eye view of unfolding technologies, these landscapes assume that the user of the roadmap or landscape is situated on the landscape. In fact, the original purpose of these landscapes was to model the search for new technologies. This allows the landscape to incorporate the cost of searches into the model. For example, a technology consumer located at O, with T1 as its current technology and with limited resources to search for a better technology, would likely find its only option in an upgrade from T1 to T2. The scope of that search is represented in Fig. 5 by the solid black rectangle. It would take more resources to mount a wider search (the ticked rectangle) to uncover the greater value of T3 and T4, represented by the higher hills B and C.

If T1–T2 represented a succession of Windows technologies, then T3 and T4 might stand for versions of Linux. A small company with limited IT expertise concentrated on Windows would not search far for its next technology. Linux would be beyond its radarscope. It simply lacks the absorptive capacity[3] to consider and benefit from more distant technologies [12,13]. A more IT-savvy organization might have the absorptive capacity to consider Linux but

[3] The concept of absorptive capacity has always struck me as an input-oriented corollary to W. Ross Ashby's output- or control-oriented law of requisite variety. The former postulates a minimum internal knowledge and understanding required to take advantage of external information, research, and components, while the latter defines the minimum internal complexity required to control an external system or entity.

would be equally at a loss if T3–T4 represented mainframe technologies. Thus, the concept of absorptive capacity, when implemented in technology landscapes provides a useful measure of a firm's capability with respect to taking advantage of research and innovations outside the firm.

There could be additional landscapes as well as other feedbacks. The product layer of a roadmap may well have its own landscape. That layer could feed back into the technology landscape to reflect the performance measures that the various technologies have been able to achieve in concrete products. One must also keep in mind that what is the technology layer to some could be the product layer for others.

These landscapes carry the theoretical issues of the cost of searching into the practical sphere by reminding us that valuations are observer dependent. A roadmap with identical elements will yield different landscapes for different companies, depending on their respective locations on the landscape. Composite technology landscapes that aggregate many individual landscapes would reflect the marketplace. They must be compiled, interactively and real-time, through a technology roadmap or innovation exchange.

8. e-Commerce in technology roadmaps elements: coevolution of markets and technologies

Trade-in technology roadmap elements would take virtual innovation to new heights. If a company came up with an innovation that did not fit its long-term plans because it lay outside its core competencies, it could post the innovation in the form of a partial technology roadmap on the technology roadmap exchange. Potential buyers would bid on the technology roadmap and the company would eventually recoup some of its R&D investments.

The final auction price of a technology roadmap containing a virtual innovation would also provide an immediate measure of the value of the innovation and its possible market. Additionally, a wide-open exchange may allow potential customers to provide the kind of product feedback that could show the foolishness of going to market. This becomes critical in industries where the time value of innovation has shrunk to where innovations create competitive advantage for distressingly little time. Time to market, which depends more on supply chain management than innovation, and timely decisions about taking a product to market in the first place determine product success. A technology roadmap exchange would be in an excellent position to compile the composite map reflecting the coevolution of technologies and markets.

Trade in technology roadmaps would also encourage patent and bibliometric clearing houses to provide new technology elements to their subscribers. This would further increase the value of the exchange. It would also present some additional challenges since patents and research are at a lower level than the elements of technology roadmaps. Until means can be devised to roll up patent and bibliometric information into technology roadmap elements, intermediary services may have to collect patents and research into components suitable for the top-down technology roadmaps.

Collaboratively developing and maintaining technology roadmaps and certainly running a technology roadmap exchange require standard technology roadmap documents.[4] These documents could contain a single element, an entire branch in a technology roadmap, perhaps including some virtual innovations, or an entire roadmap. Composite roadmaps would need methods for merging technology roadmap documents by recognizing matching elements and connecting the roadmaps at their common nodes.

Someone might argue that publishing virtual innovations or partial roadmaps erodes a company's competitive advantage by alerting competitors to the company's intentions. What a company may lose in competitive advantage, it will likely more than make up for by gaining interactive access to the market's reaction, by seeing how potential customers react to published roadmaps, and by learning what they do with those roadmaps. Consequently, the value of access to the exchange's technology landscape will far exceed any loss in competitive advantage.

9. Patterns of the evolution of technologies and products

A growing number of empirical studies point out patterns inherent in the evolution of technologies. While managers often recognize these patterns instinctively, roadmaps developed with object technology could detect them automatically and systematically. In fact, once technology roadmaps are persisted through object technology, the objects themselves could be made to recognize patterns to which they belong.

One such pattern is the growth of sustaining technologies that is punctuated by the rise of disruptive technologies [14]. Although difficult to detect in advance, the pattern arises whenever a new technology or product leads customers to reevaluate their preferences for an existing product's attributes. In that case, market M1 in effect collapses and merges with market M2, which was originally a niche market for P6 (Fig. 6a). Deprived of a market or left with a marginalized market M1, the sustaining product chain P1–P3, including its next generation, P7, collapses and terminates. By detecting sustainable technologies, especially those facing extinction, technology roadmaps could draw attention away from them to fruitful areas to search for other, potentially disruptive technologies, what Galvin called the promise of the "white spaces".

A related pattern concerns generation skipping. Failed product generations frequently contribute to the learning that makes a subsequent product a huge success, as illustrated by Maidique and Zirger [15]. Where these failures arise from design flaws, virtual innovation provides a solution. Frequently, failed product generations are due to a misreading of the market either because the market is changing or because the market is not ready to absorb another product generation. When too many product generations appear in rapid succession, it may be time to skip a generation (as P4 in Fig. 6b). The P4 object could detect that it comes

[4] A Technology Roadmap Integration, Collaboration, and Standardization Initiative was launched in conjunction with PICMET'03.

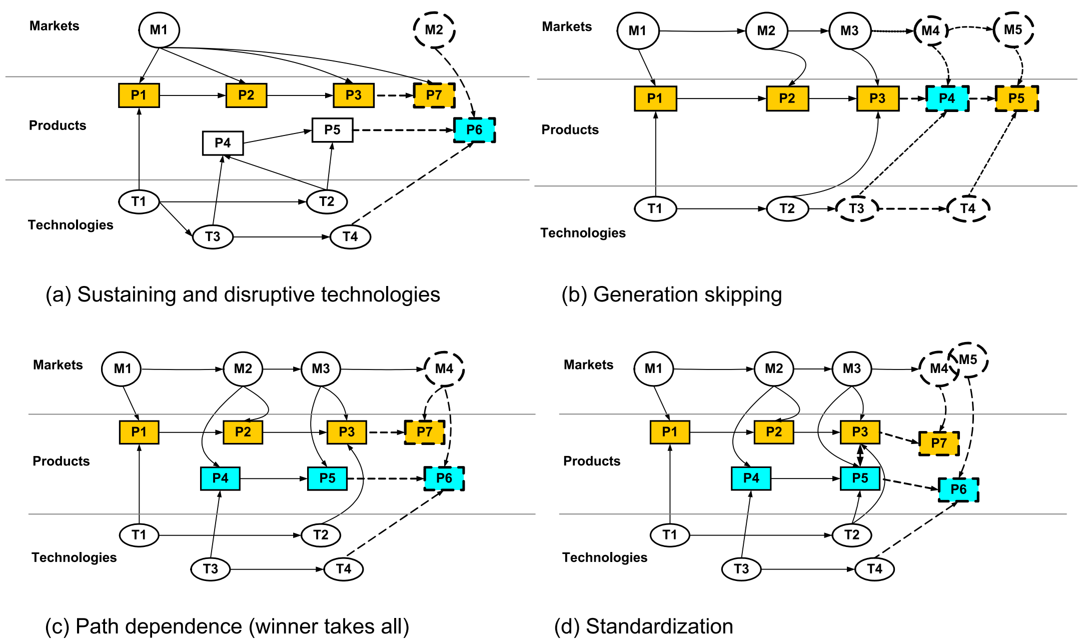

Fig. 6. Patterns of the coevolution of technologies, products, and markets. (a) Sustaining and disruptive technologies. (b) Generation skipping. (c) Path dependence. (d) Standardization.

too close on the heels of P3, with P5 just around the corner, and could flash a warning on the roadmap that generation skipping is indicated.

The adoption of competing technologies often manifests a pattern that shows path dependence [16]. In those cases, a winner usually emerges that comes to dominate the market, often as a result of a crucial event turning an indeterminate situation into an advantage or because of a first-mover advantage. Although the Apple and the IBM PC emerged around the same time and may at one time have had equal chances at grabbing market share, the IBM PC soon came to dominate the market. The Netscape and Microsoft web browsers provide another example. The pattern would be one of shrinking market share in the succession of markets M1–M4 (Fig. 6c).

A winner-takes-all outcome can be avoided through standardization (P3 and P5 in Fig. 6d). Because standards reduce lock-in, they shift the locus of competition from an early battle for dominance to a later battle for market share [17]. Technology consumers are no longer faced with the possibility of buying into the wrong standard, but are freed to choose the best-performing product. Similarly, technology providers avoid the risk of becoming a late-mover. The PC market did not really take off until Dell and others standardized the components. Standardization plays a similar role in software technology, where lack of standards puts consumers on the fence, while early standardization promotes product development and competition.

If the technology and product elements of roadmaps could detect these patterns and if they contained methods for reacting to those patterns, they could then adjust their attributes and relationships with other nodes accordingly. A product node at the end of a long chain of similar products could signal the need for generation skipping. It would also notify its associated market node to lower its expected return. Other products competing for that or similar markets may perceive this as an opportunity for themselves and raise their expectations for market share and returns. Detecting and acting on these patterns would dramatically alter the associated technology landscape. In the case of recommended generation skipping, the technology providers may then need to search farther afield on the technology landscape to find new technologies to turn what would have become an upgrade of questionable value and profit into a killer application.

10. Toward self-organizing technology roadmaps

A technology roadmap configured as an agent model could explore the interactions of the behaviors of its elements. Product agents could consume technology agents and compete with like or similar product agents for a market. Occasionally, a radically new technology could appear much like fortuitous inventions. Mostly, though, the more mundane behaviors that characterize incremental and architectural innovation would be acted out. With simple rules like these, it should be possible to "grow" a technology roadmap much like agent models have been used to grow artificial societies [18]. The behavior of the agents, in this case, would determine the structure of the system and the resulting technology roadmaps would show the effects of self-organization.

Naturally, one cannot grow a technology roadmap that faithfully reproduces the history of technology, not even of a tiny segment of that history. The value of growing technology roadmaps lies in studying the emerging properties of this self-organization. It should also yield insights into the coevolution of technologies and markets and the variance of possible futures. It would at any rate invest technology roadmaps with simulation capabilities.

11. Conclusion: a technology roadmap for the innovation game

A collection of articles introduced under the heading "A Game Experience in Every Application" in a recent edition of *Communications of the ACM* [19] calls attention to efforts in various areas of application design to incorporate game-like interfaces. Often motivated by the desire to converge training and real-world execution, gaming interfaces are increasingly recognized as tools to improve the operator's experience apart from conditioning it during training. Even mundane applications such as sales systems would turn sales agents into more productive sales people by having them play the sales game. Perhaps the game experience would give the sales agent new insights into playing win–win and win–lose games with the customer.

Following this train of thought, technology roadmaps, once provisioned with a suitable implementation infrastructure, could become innovation games. Technology consumers could play the technology selection game. They would cruise over the technology landscape looking for the highest hills in search of the best technologies for their enterprises. If nothing looked promising, they could use architectural innovation to drag and drop several promising technologies into a new virtual innovation node. This would alert potential technology providers to an opportunity while giving them a head start with a good picture of what the customer had in mind.

A technology provider might then see how well the vaguely conceived virtual innovation fits his own repertoire of innovations. That provider may decide to create a virtual prototype to gauge the size of a potential market, eventually updating the composite picture drawn by the technology customer with a far more detailed prototype, but deciding against investing any more effort. Another provider, navigating an overlay of his company's technology roadmap with the exchange's composite technology roadmap, may see an opportunity. Scanning the technology landscape for additional technologies, he may find and integrate an otherwise unrelated technology. The decision maker at that company could use the agent modeling capabilities to see how the technology roadmap, left to its own devices, would grow and what the role of the proposed product on that artificial technology roadmap would be before committing resources to develop the product.

Technology roadmaps are gaining momentum because they connect technologies, products, and markets at the right level of abstraction. Given a suitable infrastructure that supports virtual innovation and innovation factories, technology landscapes to measure the value of its elements, and roadmap nodes that participate in the management of the roadmap itself, technology roadmaps have the potential to become the infrastructure for innovation.

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