R&D/Technology Management: A Framework for Putting Technology to Work

William B. Rouse, Fellow, IEEE, and Kenneth R. Boff

Abstract—This article summarizes and integrates the state of knowledge of R&D/technology management. The goal is to clarify what is known and discuss how this knowledge can be leveraged. The overall conclusion is that understanding at multiple levels is key to deeply understanding R&D/technology management. Furthermore, these multiple levels of understanding can be integrated by considering information access and utilization throughout these processes. Specific conclusions are summarized in terms of key issues, central questions, and tradeoffs.

Index Terms—Information systems, knowledge management, R&D management, technology management.

I. INTRODUCTION—CHALLENGES AND CONTEXT

In recent years, the role and value of R&D/technology investments have been seriously challenged and reconsidered, e.g., [15] and [76]. The yields of these investments are perceived to be unacceptably low and very slow—too little too late is a common criticism. The impact on R&D/technology budgets has been quite direct and often substantial. Put simply, these budgets are no longer viewed as entitlements.

At the same time, however, there is widespread agreement that technological innovation is a key to economic growth. Companies are increasingly focused on assuring that they secure returns from their R&D/technology investments [53]. Universities are facing increasing pressure to foster knowledge-based spinoffs if their public budgets are to be assured [23]. Clearly, putting technology to work is a widely shared goal.

Deciding upon the best R&D/technology investments is far from straightforward. A central limitation is the fundamental fact that these investments often pay off in ways that are not envisioned when investments are initially made [64]. Many technologies take long and very crooked paths from invention to market innovation [14]. Thus, the very nature—not just the timing and magnitude—of returns is uncertain.

Another factor is the low yield of such investments. Perhaps one-in-ten investments pays off substantially—hopefully enough to recoup all ten investments [66]. A primary difficulty, however, is identifying emerging winners. All too often, both industry and government organizations continue to pump resources into efforts that will not yield significant returns, primarily because this issue is seldom seriously addressed once investments have begun.

These factors lead organizations to focus on creating the culture and climate for the unpredictable to emerge and creating mechanisms for recognizing it when it happens. This involves considerations both internal to R&D/technology organizations and external in the broader company or government agency. As discussed later, creating the desired culture, climate, and mechanisms tends to be much more difficult than might be imagined.

To understand the challenges outlined thus far—and be able to address them—it is important to consider the broader context of R&D/technology functions and projects. This includes the roles of R&D/technology in private and public enterprises as well as roles of these enterprises in the economy and society (see Fig. 1).

This broad context can be viewed at several levels, as follows.

- Social and political forces determine the context within which R&D/technology investments occur and strongly influence perceived rewards, risks, and tradeoffs.
- Economic factors determine the financial climate for investment in terms of availability of capital, taxes on returns, trade policies, and so on.
- Industry/market trends and factors determine opportunities due to market maturity, number of competitors, basis of competition, and so on.

Fig. 1. Broad context of R&D/technology management.
• Enterprise characteristics, such as size, profitability, innovative tendencies, and so on, affect the types of investment alternatives considered and the level of resources committed.
• Functional attributes, including forms of management (e.g., function versus project) and relationships among functions (e.g., engineering, marketing, and manufacturing), affect both technical and market success.

This broader view helps us to more clearly define what is meant by “technology” as well as what is meant by “putting it to work.” Technology is not just high tech, but includes all methods and tools for doing “business,” ranging from manual procedures to sophisticated automation. Technology can be put to work in a variety of ways, including products, processes that yield products, and policies that govern characteristics of products and processes.

A. Overriding Issues

In this article, we address several overriding issues. First, we explore the nature of technology and innovation—both the process of how they relate and how this process can be enhanced. Macroviews and microviews are considered, ranging from the general social and economic impacts of technology to the specifics of R&D/technology management. Models, methods, and tools are discussed that can aid understanding and management of these processes.

We also address the nature and roles of information in R&D/technology management, including both the means for accessing and utilizing information. Information is the currency of R&D/technology management. The transfer of this currency among stakeholders in the R&D/technology value chain is central to investments yielding returns. Specifically, transformations from data to information to knowledge to practice are central to the understanding necessary to enhancing essential management processes.

The roles of people and organizations are also central to the discussions in this article. People and organizations are almost always both the enabling and limiting factors in putting technology to work—technology, in itself, is seldom the difficult part. Understanding these types of issues is essential to realizing the full potential of R&D/technology investments.

Finally, we focus on the issue of the value of R&D/technology investments. Perceptions of value strongly influence behaviors of investors, managers, and marketplace decision makers. We discuss approaches to assessing value, performing value tradeoffs, and managing the overall value creation process.

B. Organization of Article

The article is organized in four sections. We begin with the Macroview—Social and Economic Perspectives. This section explores the broad social, political, and economic context of technological innovation, including the circumstances most fertile for R&D/technology investments. This section also considers specific economic factors and indicators associated with these investments.

II. MACROVIEW—SOCIAL AND ECONOMIC PERSPECTIVES

We next focus on the Microview—Enterprise and Functional Perspectives. This section focuses on the roles of R&D/technology in both private and public sector enterprises. Factors that influence success—or failure—of investments are discussed. Management of R&D/technology functions and projects is considered in terms of the degrees of freedom and constraints that typically affect managers.

Our attention then shifts to the Information View—Access and Utilization. This section emphasizes the pervasive nature of information and how R&D/technology investments are ultimately made to yield information, knowledge, and skills that provide competitive advantages in the marketplace, versus adversaries, or for solving problems. This section also focuses on mechanisms for accessing information as well as methods and tools for utilizing information.

We conclude by addressing Key Issues, Central Questions, and Tradeoffs. This section provides practical guidance and recommendations for addressing major issues in R&D/technology management. These issues include formulation of objectives, generation of projects, allocation of resources, transfer of technology, and design of the organization. The ways in which these issues are best addressed are discussed in the context of an overall investment model that illustrates tradeoffs among investments to enhance an enterprise’s technology, product, customer, and market bases.

A. Broad Context of Technological Innovation

Mokyr [46] considers how technology can be the “lever of riches” that results in formation of new industries and opportunities, particularly when there is a confluence of enabling factors. He provides an historical treatment of the seeds of such major historical events as the Industrial Revolution, where
clusters of “microinventions” yielded enormous economic returns. He focuses in particular on factors that differentiate times of substantial returns from times when inventions do not yield such returns.

Mokyr identifies several major inhibiting factors. Inventions are much less likely to lead to market innovations when society exhibits an aversion to disrupting the existing economic order. A low ranking of economic activity in the social order is also a strong inhibitor—causing the “best and brightest” to pursue endeavors other than business.

Other inhibitors include change generated mainly by the public sector and a lack of human capital. Government is notably ineffective at promoting transitions of inventions to market innovations. On the other hand, government can invest in the long-term growth of human capital via, for example, educational programs and incentives. Thus, government can have an indirect role but performs poorly when trying to directly influence the process.

Wallace’s studies of innovation in the United Kingdom led to identification of several factors that foster innovation [77]. He concludes that there is a need for institutions that 1) survive over two or more generations, 2) control or have access to redundant resources, and 3) regard support of innovation as investments in best practices. Also important is a general ambiance of encouragement of technological innovation. Finally, he points out a need for a porous social structure that supports inventive artists and innovative entrepreneurs.

Rouse [60] presents case studies of three industries—transportation, computer, and defense over the past 200 years. He discusses the factors influencing the successes and failures of the thousands of companies formed in these industries over this period. He concludes that companies’ abilities to recognize changing relationships with evolving markets are key to continued success. A central dilemma is the strong tendencies of companies that become institutions to cling to past relationships and hence pursue inherently limiting strategies. This tendency would seem to interact with several of the factors identified by Mokyr and Wallace.

Thus, social, economic, and political characteristics strongly influence when technology innovations happen and the extent to which they are sustained. These characteristics not only vary in time—they also vary geographically. The preeminent location of innovation in our times is Silicon Valley in northern California [45], [56]. This area exhibits the above supporting factors more strongly than any other place in the United States and probably elsewhere.

A close second was Route 128 in Boston, MA. However, as Saxenian [68] ably describes, the more conservative culture of Boston hindered it from achieving the resilience of Silicon Valley. For example, the relatively low rate of employee turnover at Route 128 companies—relative to Silicon Valley companies—retarded the speed at which new technologies diffused through these companies. This speed provided Silicon Valley companies with substantial advantages.

Several areas in the United States have pursued the Silicon Valley model. Research Triangle, NC, and Austin, TX, are two of the more notable. Back in the pack a bit is Atlanta, GA, which has in recent years acquired many of the necessary characteristics [61]. Of course, factors that correlate with technological innovation do not necessarily cause technological innovation. Thus, imbuing an area with many of the characteristics of Silicon Valley will not necessarily yield similar economic results.

The ways in which technologies emerge, mature, and are eventually adopted reflect an unpredictable set of processes. As noted earlier, these processes often result in returns that are unexpected in nature, not just timing and magnitude. Further, as Burke [14] convincingly illustrates, these returns are often realized by people other than the original investors.

Consequently, predicting the specific returns likely from investments in technology is akin to predicting the unpredictable. Aside from clairvoyance, the key to dealing with this dilemma is developing the ability to recognize that the unpredictable has happened and translate this recognition into strategies, plans, and actions. This may also allow anticipating opportunities. For example, in some cases, demographic trends make it such that the future has, in effect, already happened [25].

The issues discussed in this section have clear implications for R&D/technology management. Few managers can significantly influence the economic culture and climate affecting their organizations. However, they can develop an explicit understanding of these forces and adjust their expectations accordingly. For instance, a manager can increase his or her likelihood of success if they understand—and prepare for—an uphill battle to gain the support of their conservative corporate culture.

Thus, the broader view presented in this section provides support for realistically assessing the situation faced by R&D/technology investments. Not understanding where you are and the forces you face can completely undermine abilities to meet expectations. On the other hand, understanding that key stakeholders do not view R&D/technology through the same glasses as aficionados can help to frame expectations and tailor the business story necessary for success.

B. Economic Factors in Investment

As shown in Fig. 3, the ability to translate market opportunities into technology investments depends on a variety of factors. Economic policies, including fiscal, monetary, trade, and tax policies, strongly affect the investment climate. Resources in terms of labor, management, and capital also play key roles.

Economic analyses of likely returns from R&D/technology investments usually address one or more of three types of uncertainties: time, magnitude, and nature of returns. The time until returns are realized is often quite long. For example, academic research typically requires 20 years until economic gain [2]. Investments over this time horizon are obviously difficult to justify in terms of traditional net present value calculations. Almost any reasonable discount rate, when compounded over 20 years, yields near-zero present value. This often results in long-term projects being axed [54].

For this reason, much shorter time horizons are usually sought. In addition, other factors may be considered in the decision making process. For example, R&D/technology in-
Numerous studies have focused on these factors—see reviews by Cohen et al. Although government fiscal, monetary, trade, and tax policies strongly affect companies’ technology investments for purposes of creating market innovations, in particular, the time horizons that companies adopt for evaluating these investments are strongly related to the cost of money and investment incentives. For example, monetary policies that allow relatively high rates of inflation tend to increase discount rates and shorten time horizons.

Another economic consideration is people’s proclivities to choose careers in science and technology. As Diamond summarizes, incentives and rewards on the individual level affect people’s willingness to choose such careers, and, hence, the stock of human capital available for pursuit of R&D/technology projects. Thus, economic considerations govern behaviors on multiple levels.

It is important to note that R&D/technology investments not only serve the purpose of gaining competitive advantage in the marketplace, but they can also serve social purposes—for example, to inform policy makers and influence policy decisions. Despite the much more ambiguous causal chain between investments and social returns, it has been shown that such returns are often much higher than what the private sector experiences.

The practical implications of this discussion of economic factors are quite clear. The smaller the portfolio and the fewer the number of investors—especially when one project is being considered by one investor—the less the uncertainties must be economically justified. This means that shorter time horizons and more predictable magnitude and nature of returns become more important. Put simply, when the risks cannot be spread and shared, we have to focus on reducing risks.

III. MICROVIEW—ENTERPRISE AND FUNCTIONAL PERSPECTIVES

In general, larger firms in technology-competitive markets and industries tend to invest more heavily, although smaller firms in these markets and industries often invest a higher percentage of revenues in R&D/technology projects.

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III. MICROVIEW—ENTERPRISE AND FUNCTIONAL PERSPECTIVES

The macroperspective discussed thus far is important to an individual enterprise’s point of view in terms of the effects of macrovariables on the enterprise’s alternatives, constraints, and prospects. Understanding these factors is important to an enterprise adopting reasonable and realistic market assumptions. However, most of the variables that an enterprise can manipulate are at the microlevel within the enterprise and its internal functions.

Numerous studies have focused on assessing the impacts of a wide variety of independent variables on dependent variables at this level. Tables I and II summarize the variables studied in 25 key empirical studies reviewed by Rouse et al. [65]. As Table I indicates, dependent variables studied were dominated by market success and technical success, with activities, budget and schedule performance, commitment/satisfaction, structure, and time also receiving attention. From Table II, it can be seen that independent variables studied include com-
TABLE I
DEPENDENT VARIABLES AND SOURCES OF EMPIRICAL STUDIES OF THESE VARIABLES

<table>
<thead>
<tr>
<th>Class of Variable</th>
<th>Dependent Variable</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activities</td>
<td>Use of information</td>
<td>Hamer &amp; Nihila (1997)</td>
</tr>
<tr>
<td>Activities</td>
<td>Initiation of innovations</td>
<td>Abbey &amp; Dickson (1983), Scott &amp; Bruce (1994)</td>
</tr>
<tr>
<td>Budget Performance</td>
<td>Allocation of funds</td>
<td>Brockhoff &amp; Schmaul (1996), Mansfield &amp; Brandenburg (1996)</td>
</tr>
<tr>
<td>Commitment/Satisfaction</td>
<td>Job involvement</td>
<td>Gerpott, Dorosh &amp; Pearson (1986)</td>
</tr>
<tr>
<td>Commitment/Satisfaction</td>
<td>Job satisfaction</td>
<td>Gerpott, Dorosh &amp; Pearson (1988)</td>
</tr>
<tr>
<td>Commitment/Satisfaction</td>
<td>Weekly hours on job</td>
<td>Gerpott, Dorosh &amp; Pearson (1988)</td>
</tr>
<tr>
<td>Market Success</td>
<td>Benefits of external relations</td>
<td>Cooper &amp; Kleinschmidt (1996)</td>
</tr>
<tr>
<td>Market Success</td>
<td>Satisfaction with opportunities and rewards</td>
<td>Abbey &amp; Dickson (1993), Balachandra (1999)</td>
</tr>
<tr>
<td>Market Success</td>
<td>Satisfaction with supervision</td>
<td>Abbey &amp; Dickson (1993), Balachandra (1999)</td>
</tr>
<tr>
<td>Market Success</td>
<td>Project performance</td>
<td>Katz &amp; Allen (1985)</td>
</tr>
<tr>
<td>Market Success</td>
<td>Project quality</td>
<td>Azumi &amp; Hall (1990), Balachandra (1999)</td>
</tr>
</tbody>
</table>

The references indicated in Tables I and II, in addition to numerous related sources, report hundreds of findings of relationships between the independent and dependent variables summarized in these tables. It is not possible within the confines of this article to summarize and discuss this breadth of findings. However, by focusing solely on predictors of technical success and market success, a terse listing is possible.

Probability of technical success tends to be increased by increases of the following:

- size of company;
- R&D spending (as percentage of sales);
- contact with customers;
- influence of project managers (as opposed to functional managers);
- leadership by management;
- satisfaction with supervision;
- satisfaction with opportunities and rewards;
- perceived importance of work;
- educational level of employees;
- participation and cooperation;
- horizontal communication.

Probability of market success tends to be increased by increases of the following:

- profitability of company;
- competitive position of company;
- competition—both external and internal;
- management involvement and support;
- mission orientation of R&D organization;
- rewards linked to performance;
- commitment of personnel;
- fit with existing markets and products;
- fit with technology base;
- cross-functional cooperation;
- integration of R&D and marketing;
- marketing proficiency;
- project management skills.
There are subtleties that these simple lists cannot capture, including a variety of factors that tend to decrease technical and market successes. Nevertheless, these lists illustrate the nature of the types of relationships discussed in the references noted in Tables I and II.

The classes of variables indicated in these tables also provide a very useful basis for discussing the options available to enterprises as they attempt to enhance their success in managing R&D/technology. The remainder of this article explores many of these options.

A. Role of R&D/Technology in the Enterprise

As indicated in Fig. 4, the central R&D/technology issue for an enterprise is transforming alternative technology opportunities into a successful portfolio of technology investments. The processes involved include management of R&D/technology, transfer of technology to product and service lines, and integration of technology to maximize the success of these product and service lines. Resources employed in these processes include the enterprise’s market position, technology base, and competencies.

A variety of management issues are central to the transformation depicted in Fig. 4. Enterprises have to—or should—assess current and emerging market and/or technology situations, identify alternative courses of action, predict likely consequences, make resource allocation decisions, and commit and manage resources. In particular, a key factor in the success of this transformation is managing for results. Put simply, R&D/technology investments tend to yield higher returns when these investments are premised on explicit market-based expectations for resulting technologies.

The desirability of managing for results presents an enormous dilemma. As noted earlier, a central challenge in R&D/technology management stems from the difficulty of predicting the unpredictable—the timing, magnitude, and very nature of returns from R&D/technology investments are inherently substantially uncertain. Hence, an important organizational competency, also discussed earlier, is the ability to recognize the unpredictable when it happens and then take advantage of this opportunity. This tends to broaden the nature of the yields exploited and, hence, increase the overall magnitude of returns.

How can we manage for results, while also accepting the great likelihood that the most important results are unpredictable? Balance is the answer. Formulation and execution of R&D/technology plans are crucial to achieving the focus necessary to creating returns on investments. At the same time, an enterprise has to be open to discovering new ways to realize

TABLE II
INDEPENDENT VARIABLES AND SOURCES OF EMPIRICAL STUDIES OF THESE VARIABLES

<table>
<thead>
<tr>
<th>Class of Variable</th>
<th>Independent Variable</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company</td>
<td>Competitive position</td>
<td>Krogh, et al. (1988)</td>
</tr>
<tr>
<td>Company</td>
<td>Levels of innovation</td>
<td>Abbey &amp; Dickson (1983)</td>
</tr>
<tr>
<td>Company</td>
<td>Profitability</td>
<td>Balachandra (1989)</td>
</tr>
<tr>
<td>Company</td>
<td>R&amp;D spending (as a percentage of sales)</td>
<td>Azumi &amp; Hui (1990), Baker, et al. (1986)</td>
</tr>
<tr>
<td>Management</td>
<td>Resources (both people and money)</td>
<td>Balachandra (1989), Cooper &amp; Kleinschmidt (1996)</td>
</tr>
<tr>
<td>Management</td>
<td>Changing objectives</td>
<td>Cooper &amp; Kleinschmidt (1996)</td>
</tr>
<tr>
<td>Management</td>
<td>Focus on profit maximization</td>
<td>Mansfield &amp; Brandenburg (1966)</td>
</tr>
<tr>
<td>Management</td>
<td>Influence of project managers</td>
<td>Katz &amp; Allen (1985)</td>
</tr>
<tr>
<td>Management</td>
<td>Leadership</td>
<td>Keller (1992)</td>
</tr>
<tr>
<td>Management</td>
<td>Management accountability</td>
<td>Song, Montoya-Weis &amp; Schmidt (1997)</td>
</tr>
<tr>
<td>Management</td>
<td>Risk taking</td>
<td>Mansfield &amp; Brandenburg (1966)</td>
</tr>
<tr>
<td>Management</td>
<td>Satisfaction with supervision</td>
<td>Keller, Julian &amp; Kedia (1996)</td>
</tr>
<tr>
<td>Management</td>
<td>Transfers of personnel</td>
<td>Baker, et al. (1996)</td>
</tr>
<tr>
<td>Market</td>
<td>Assured availability of raw materials</td>
<td>Balachandra (1989)</td>
</tr>
<tr>
<td>Market</td>
<td>Chance events with positive impact</td>
<td>Saliah &amp; Wang (1993)</td>
</tr>
<tr>
<td>Market</td>
<td>Early external competition</td>
<td>Balachandra (1989)</td>
</tr>
<tr>
<td>Market</td>
<td>Internal competition</td>
<td>Mansfield &amp; Wagner (1975)</td>
</tr>
<tr>
<td>Market</td>
<td>Internal customers</td>
<td>Mansfield &amp; Wagner (1975)</td>
</tr>
<tr>
<td>Market</td>
<td>Market success temporary</td>
<td>Song, Montoya-Weis &amp; Schmidt (1997)</td>
</tr>
<tr>
<td>Market</td>
<td>Probability of success</td>
<td>Song, Montoya-Weis &amp; Schmidt (1997)</td>
</tr>
<tr>
<td>Market</td>
<td>Uncertainty about market</td>
<td>Chessa (1990), Meyer &amp; Utterback (1995)</td>
</tr>
<tr>
<td>Market</td>
<td>Unfavorable government regulations</td>
<td>Balachandra (1989)</td>
</tr>
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</table>
returns. The requisite balance involves maintaining focus on goals and relentlessly executing plans for achieving these goals—while at the same time being open to new pathways to success and ready to rapidly reallocate resources.

This balance is, admittedly, very difficult to attain and maintain. As Christensen [17] illustrates, abilities to recognize technology breakthroughs do not inherently lead to success. Large, established enterprises often find it quite difficult to accept and integrate new technologies into their systems, products, and services. Pressures to sustain growth in existing lines of business often preclude investing in nascent technologies that, in the short-term, represent relatively small opportunities.
In the long-term, however, large enterprises often suffer or fail when such “disruptive” technologies eventually mature.

There are a variety of approaches to the issues just outlined. The overriding philosophy is common—R&D/technology investments should be driven by long-term needs of markets/stakeholders, including emerging long-term opportunities to address new needs. In this section, we discuss approaches that relate to the overall enterprise; in the subsequent section, we consider approaches focused on the R&D/technology function.

One group of approaches emphasizes market-driven product planning and design as the basis for determining R&D/technology needs and opportunities [5], [59], [73]. By focusing on long-term market needs, as well as opportunities to meet new needs, these approaches drive R&D/technology plans. The primary limitation of these approaches is management’s abilities to envision future market needs, especially yet-to-emerge needs.

Another group of approaches pays more attention to technology and less to products per se [18], [28], [43], [66]. These approaches focus on relationships among key stakeholders (e.g., engineering, marketing, and top management) and creation of cultures of innovation that support the transition of new technologies into product and service lines. This creation process is supported by innovation audits [28], innovation scorecards [18], and organizational IQ tests [43].

A wealth of tools is associated with both groups of approaches. Tools for market modeling, technology roadmapping, project selection, and portfolio analysis are notable examples. While there are no formal tools for addressing the balance dilemma noted earlier, this issue is addressed by several of these authors in terms of leadership and its role in attaining and maintaining balance.

A central issue addressed by many authors concerns the need to manage R&D/technology throughout the process of creation and implementation for high levels of return to be realized [47]. Particular attention should be paid to intraorganizational technology transfer and innovation [75]. It can be surprisingly difficult to transition technology into use across organizational units, often because no one has action-level responsibility across units.

Technology integration is also a very important aspect of R&D/technology management. Integration often is key to achieving yields much greater than the sum of the parts as well as central to achieving significant competitive advantage [32]. In fact, the parts may not play together at all without careful attention to integration. For this reason alone, management should assure that integration is high on the agenda long before it is on the critical path.

Time horizons chosen for technology investments affect what investments are made and how they are managed. Factors affecting time horizons include composition of boards of directors, compensation of senior management, attitudes of institutional investors, and federal roles in terms of tax policies and budgets [49]. When time horizons are very limited, many of the concepts and methods discussed in this section are of less relevance since, in effect at least, potential returns from R&D/technology investments have been completely discounted.

B. Managing R&D/Technology Functions and Projects

As noted in Section I, the era of academically oriented industrial R&D/technology organizations appears to be ending—budget “entitlements” are over and managers in these organizations now have to manage rather than just monitor and occasionally harvest. These managers increasingly have to sell their efforts in terms of their likely impact on business goals. This requires that they focus on getting the applied world to the laboratory door [57].

Making such “sales” is complicated by the moving nature of the target. R&D/technology managers consequently have to align their efforts with new product development management practices. These practices include product line concepts [13], modularity [8], and dramatically decreased development cycle times [31]. Rather than just finding a “home” for new technologies in a single new product, managers have to position these technologies as key elements of integrated architectures.

The process of becoming relevant and valued in such a dynamic world also requires that R&D/technology managers bring good management practices to their organizations. This dictates substantial changes for many organizations, particularly government and academic R&D/technology organizations [33]. For example, the former focus on inputs (i.e., budgets and staffs) has to shift to outputs (i.e., fielded technologies).

Many organizations are moving to—or at least entertaining—new business models. For example, Roussel et al.’s third generation R&D model [66] emphasizes general managers and R&D/technology managers working as partners to create the best portfolio of R&D/technology activities for the corporation. Another instance is Cohan’s leadership model [18], which focuses on entrepreneurship, open technologies, product development, and resource allocation. The approach of Matheson and Matheson [43] emphasizes R&D best practices, including the organizational changes and support systems needed to adopt these practices.

In general, now more than ever, R&D/technology managers have to understand the forces affecting their project portfolios.
and husband the resources necessary for the projects in their portfolios to maximize both technical and market success. As shown in Fig. 5, forces include market attributes, company characteristics, and a variety of management factors. Resources all pertain to people and include skills and abilities, motivation and incentives, and methods and tools. Clearly, purely focusing on understanding technology is no longer an adequate prescription for success.

Beyond the classes of factors depicted in Fig. 5—and the specific instances summarized in Tables I and II—a variety of overriding principles have been identified. For example, Souder [73] discusses ten principles for managing innovations. Ransley and Rogers [55] discuss R&D best practices in terms of seven factors. The National Research Council [50] has identified five pillars of world-class R&D organizations, including the organizational characteristics and metrics needed to foster these characteristics. Finally, Zien and Buckler [79] discuss seven principles for creating a culture of innovation.

These four sets of principles are by no means the only prescriptions available on this topic. However, they are representative. Further, they are also fairly similar, although not all are expressed at the same level. Combining these four sets of 29 principles results in the following set.

- **Communication**: Foster communication between R&D and marketing as well as across the whole organization; consider using powerful and purposeful stories.
- **Competition**: Monitor external threats, making use of a wide variety of information sources.
- **Customers**: Focus on needs, opportunities, and levels of sophistication as well as intimacy, quality, and value.
- **Management**: Avoid tendency to force projects into standard boxes, and adapt processes to the nature of opportunities and innovations.
- **Measurement**: Measure results against technology and business objectives.
- **Organization**: Avoid classical organizing approaches and structure relationships to foster real communication and cooperation.
- **Patience**: Prepare for possibilities of uncertain and lengthy paths from investments to success.

**Project Selection**: Develop and utilize a systematic process for identifying and selecting projects and assessing the resulting portfolio.

**Resources**: Pay careful attention to the human, financial, and technology resources required for investments to succeed.

**Strategy**: Create and communicate an integrated business and technology strategy.

**Technology Transfer**: Assure internal technology transfers by utilizing cross-functional teams and job rotations.

In many ways, these principles reflect the issues, studies, and results reviewed thus far. These principles also have implications for how more detailed issues should be addressed and resolved. These detailed issues are considered in a later section of this article.

### IV. Information View — Access and Utilization

The macroview and microview provide structure-oriented illustrations of the ways in which organizations and environments interact at different levels. This perspective shows how issues impact levels differently. For example, macroview returns for the economy may be acceptable, while microview returns for individual enterprises are far from acceptable.

In this section, we move away from structural interactions and focus on input/output behaviors. More specifically, we consider the “currency” of technological innovation—information. To a great extent, information can be viewed as the currency of business, in general, with dollars or equivalent being only one type of information. Management is a process of accessing and utilizing information—via both human and nonhuman means—to assess, predict, control, reward, and guide the organizational phenomena of interest.

For R&D/technology management, information influences what efforts are undertaken and, to a great extent, constitute the nature of the outputs of these efforts. On the input side, the gathering, sharing, and utilizing of market information has been found to be highly related to the subsequent success of new product efforts [52]. Efforts that are underinformed relative to market needs and forces are much more likely to yield disappointing returns.

On the output side, information about technology and how it can be employed is usually valuable in itself and the economics of information is playing an increasingly central role in management [26]. Investments in R&D/technology seldom yield finished technological artifacts. Instead, they produce demonstrations of feasibility, benefits, and costs, as well as knowledge and skills, to support subsequent applications.

#### A. Information Access

Key to information access is the concept of the value of information. As indicated in Fig. 6, information is valuable to the extent that it is relevant to the user’s needs, available in suitable forms of presentation, and easy to interpret [10], [11], [58]. In other words, to be valuable, information has to be useful and usable.

These criteria explain Allen’s [3] finding that 95% of an engineer’s information needs are met within 6 ft of his or
her desk, typically by another person. However, this mode of information access is totally inadequate for assessing and selecting among alternative R&D/technology investments and subsequently managing these investments. Thus, mechanisms are needed to enhance information value to assure its use.

This is particularly challenging during current times of rapidly expanding information availability via networked access to an accelerating wealth of databases and knowledge bases. There are also many alternative vendors of data warehousing and data mining. Making sense of the vast stores of market and technology information has become a priority for many enterprises.

Of course, data mining is at least one step removed from what is really wanted. Most people would gladly forego the data and instead make direct use of the knowledge that can be gleaned from this data. Thus, the real desire is knowledge mining. Rouse et al. discuss this need and illustrate how knowledge mining can help to identify current and emerging trends in markets, technologies, and management practices [65]. Balachandra shows how mining can be useful for creating project monitoring systems for assessing likely success or failure of ongoing R&D and then modifying or perhaps canceling projects if necessary [7].

Another possibility is the use of intelligent agent technology to create autonomous mining agents. These agents could, for example, search the Internet for data and knowledge relevant to R&D/technology investment decision making [38]. While agent technology is far from mature, it is quite likely that this approach to mining will eventually be very useful.

B. Information Utilization

Overall, information provides the basis for assessing where you are, forecasting trends and events, and evaluating alternative strategies and tactics for dealing with these contingencies [60]. As shown in Fig. 7, market/technology forecasting, project selection, and project monitoring are central ways in which information is utilized for R&D/technology management. These types of uses support key decisions regarding which projects are added to the overall portfolio as well as which projects are retained.

Technology roadmaps [28] and market readiness analyses can be important elements of the necessary forecasts. However, we have found that use of formal methods is the exception rather than the rule. Quite often such issues are approached in a fairly ad hoc manner, typified by informal discussions and consensus building rather than data collection. The result can be a significant risk of delusions regarding market/technology trends [63].

Forecasts often serve as inputs to project selection processes. There are a variety of methods and tools available for characterizing and selecting among alternative investments from a wide range of perspectives. Balachandra [7] discusses a variety of leading indicators of project success that are useful for both initial selection and early signs of difficulties. Much more elaborate is Cooley et al.’s [20] systems dynamics model for estimating the impact of funding levels, schedule changes, personnel workloads, and technical risk on the output of any given work unit and the overall R&D goal at any time in the future.

Souder [73] discusses five overall approaches to project selection—committee, campaign, system, proactive, and reactive—as well as four formal models—checklists, scoring models, prioritization models, and portfolio models. Souder and Mandakovic [74] discuss four types of models—classical methods, portfolio models, project evaluation techniques, and organizational decision models. Rouse et al. [64] show how cost/benefit analyses can assist managers in both understanding the relative merits of past investments and, to an extent, projecting the likely merits of alternative future investments.

There is no lack of methods and tools for utilizing information concerning the likely merits—and demerits—of alternative R&D/technology investments. Their use is limited by several factors. Often, it is perceived to be too time consuming and expensive to collect the input information for these methods and tools. It is also common for incumbency and other social factors to drive project selection decisions—information is not collected because it will not influence decisions. We return to this issue in the next section.

V. Key Issues, Central Questions, and Tradeoffs

This article has thus far broadly explored R&D/technology planning and management from both macroperspectives and
microperspectives as well as from an information point of view. The remainder of this article focuses on the implications of this wealth of knowledge from the perspective of individual managers. Put simply, we now address the overall question, "what should you do?"

From a macroperspective, a manager’s goal should be to monitor trends and events in society, the economy, and the industry/market. With the possible exception of a very few large enterprises, a manager cannot influence these trends and events. However, it is important to understand these trends and events in terms of the opportunities, problems, and constraints they imply.

From a micro point of view, managers have much more control. Top management certainly can strongly influence overall corporate goals and processes. R&D/technology managers also can influence these goals and processes. However, on the short term at least, R&D/technology managers may have to accept corporate goals and processes as “givens.”

At the level of the function/project, R&D/technology managers have their greatest control. At this level, they need to maximize their value added within the context of society, economy, industry/market, and corporation. This section addresses alternative means for achieving this end.

There are several key issues that should be addressed by both top management and R&D/technology managers, as follows:

- formulation of objectives;
- generation of projects;
- allocation of resources;
- transfer of technology;
- design of the organization.

In this section, these issues are discussed in terms of central questions and alternative answers. These answers were derived from the state-of-the-art review presented earlier in this article.

A. Formulation of Objectives

What role(s) should R&D/technology serve in the overall organization? Many managers in the past would have said that this function should serve as a “think tank,” in which a wide range of ideas are pursued and numerous inventions result. A much more common answer today is that R&D/technology functions should provide enabling technologies to support market innovations by other functional areas of the enterprise. Also common is the sense that this function should provide key competitive advantages by creating leading-edge products and processes. Thus, objectives are more directly linked to business objectives than in the past.

How should the role(s) of R&D/technology be balanced? One possibility is to have separate R&D/technology organizations for different roles. More common, however, is for all organizations to have budget allocations across all roles. Increasingly, role definitions vary with projects and are driven by market/technology needs and opportunities. The overall goal is to foster synergies among roles.

How should an R&D/technology organization prove its success? Traditionally, metrics such as number of publications and patents were predominant. Currently, however, we see much more emphasis on measurable value added from solving difficult technical and/or operational problems. Also emphasized are measurable contributions to new products and processes.

What are the advantages/disadvantages of budgeted R&D/technology versus independent profit center models? Budgeted R&D/technology organizations tend to have a broader purview, but they are often less responsive to business needs. They also are usually longer term in focus, but this focus is potentially irrelevant. Profit center models tend to be more responsive, but they usually have a narrower purview. Their efforts usually have greater business relevance, but they are shorter term. Hybrid models can balance these advantages and disadvantages and, therefore, are common.

B. Generation of Projects

How should market forces, technology trends and opportunities, and competitive benchmarks influence which R&D/technology efforts are considered? Best practices in this area include assessing current and emerging business situations, i.e., relationships with markets, analyzing assessed situations to determine current and emerging market needs and desires, mapping needs and desires to current and emerging technology opportunities, and assessing your position by benchmarking against current and emerging players. As straightforward as this sounds, few organizations do this well, in part because it takes substantial commitment to follow through on such efforts.

What is the balance between internal and external sources of ideas? As organizations mature, there is a natural tendency for a higher proportion of new ideas to be generated internally. However, if all ideas are generated internally, organizations eventually become myopic and lose track of broader trends, opportunities, and threats. On the other hand, if all ideas are generated externally, organizations risk becoming “me too” enterprises with few new ideas of their own. A useful first step in creating balance between internal and external sources is keeping track of the contributions from both sources.

How are project ideas captured and articulated? The default mechanism tends to be the grapevine, i.e., e-mail, coffee pot, etc. In some cases, brainstorming sessions and notes are used to capture ideas. Some organizations prepare memos and reports to summarize ideas. In rare cases, formal databases are developed. Without some way to capture project ideas, there tends to be regular reinventions of similar ideas.

C. Allocation of Resources

How are scarce resources (money, people, and facilities) allocated among competing projects? Resource allocation is a central issue in all organizations. Garnering resources often prompts much informal lobbying and deal making. Project incumbency is also frequently a major factor. However, numerous studies have shown that explicit criteria and some form of scoring system lead to better decisions. Such tools tend to result in more balanced portfolios relative to strategic programs and time horizons. It is also important that these
decisions include careful consideration of how plans will be executed and reviewed as they progress.

What business- and technology-related criteria influence decisions? Common financial criteria include Net Present Value, Internal Rate of Return, and Discounted Cash Flow. Cost/benefit projections may be used when important attributes are noneconomic in nature. Frequently cited criteria include the following:

- strategic fit and importance;
- competitive impact and sustainability;
- projected financial rewards;
- probability of technical and commercial success;
- R&D/technology costs and capital investments;
- time to achieve goals.

How are people made aware of this decision making process? Project selection methods and tools are only viable if people believe that they are used and make a difference. Word of mouth is particularly poor as a sole means of explaining decision making. Written documentation of processes helps, as does training in how processes work. Methods and tools that embody the processes are better yet. These processes generate the most interest when they are the required means to obtain project resources as well as when project decisions are communicated in the context of these processes.

D. Transfer of Technology

How are the results of R&D/technology investments transitioned into use? Internal technology transfer is often a difficult issue in many enterprises. The informal communication method—often termed “over the wall”—is both inefficient and ineffective. Formal publications, both company and archival, are helpful. The most effective approaches emphasize members of cross-functional project teams “carrying” technologies to applications. When combined with official project sponsor-ship, acceptance of new technologies is very much enhanced.

Are technology transition plans central to project evaluation? Not surprisingly, technology transition is more likely to happen when it is explicitly planned. While a purely Darwinian process—in other words, sink or swim—has been the norm, it is widely recognized that this process undermines returns on R&D/technology investments. Consequently, it is becoming increasingly common for explicit milestones and decision criteria for continued investment to be elements of plans. Agreements between applications sponsors and project teams are also common. Continued investments are linked to milestone deliverables and sustained project decision making.

How are unplanned applications of new technologies facilitated? As noted earlier, the greatest investment returns often occur in areas other than those originally planned. Abilities to recognize such opportunities can distinguish substantial from mediocre returns. Often this recognition and application are left to bottom-up serendipity. More effective, however, are regular reviews of trends and opportunities, both internal and external. These reviews include systematic screening processes for matching market opportunities and new technologies.

How can government-supported R&D be transitioned into commercial use? While the role of government investments in science and technology appears to be changing [9], the government nevertheless sponsors roughly half of all research investments. The results of these efforts are of potential value to most enterprises, provided that these efforts can be identified and their results accessed. A typical approach is to monitor the work of enterprises involved in these efforts, including government laboratories, and take advantage of public domain results. Many firms seek government contract R&D funding, harvest valuable results that emerge from these contracts, and support the transition of these results to commercial use. Most sophisticated are those firms that target government funding sources that support R&D/technology areas central to their long-term commercial plans.

E. Design of the Organization

How should the structure and culture of an R&D/technology organization support fulfilling its role(s) in the overall enterprise? Traditional organizational models have been borrowed from academia and involve individual staff members clustered in disciplinary areas. This model is rapidly disappearing and being replaced, initially by a hierarchical business model organized into disciplinary areas and eventually by a hierarchical business model organized across disciplines within market areas. The most dynamic and flexible models involve market-driven teams with partnerships across technologies and markets.

How should incentive and reward systems be aligned with the organization’s goals and plans? Again borrowing from academia, traditional systems are linked to individual publications and patents. Increasingly common are systems that link incentives and rewards to R&D/technology team publications and patents; project schedule and budget performance, especially deliverables; successful execution of technology transition plans; and market success of products and processes emerging from R&D/technology. Weighted composites of all of these factors are also attractive.

F. Investment Tradeoffs

Information access and utilization are central to addressing the key issues outlined above. Three aspects are critical—investment decisions, project monitoring and control, and assessment of returns. The types of information important to these issues include the following:

- **Investment Decisions**: Market trends, technology trends, competitive position, core competencies, and resource requirements.
- **Project Monitoring and Control**: Tasks, milestones, schedule and budget performance, and external trends and events.
- **Assessments of Investment Returns**: Product functions and features, sales, market share, profits, policies, and impacts.

It can be argued that the overall purpose of R&D/technology investments is to transform some of these types of information
(e.g., market and technology trends) into some of the other types of information (e.g., product functions and features).

Decisions to invest in R&D/technology projects are complicated by the interactions of these investments with other investments that enterprises must consider. In general, these investments focus one or more of the following assets of the enterprise.

- **Customer Base (CB):** The names, addresses, etc. of the people or organizations whose needs have been met, problems have been solved, etc. A typical goal is to grow the number of customers by both retaining existing customers and attracting new customers. Also important is increasing the average revenue per customer.

- **Product Base (PB):** Current products and services—or, in general, solutions. These offerings are usually “off the shelf” in that no further R&D/technology development is needed. A typical goal is to increase the number of successful solutions and decrease the average age of these solutions.

- **Market Base (MB):** Understanding of current and projected needs of existing markets (or constituencies) and broader markets as well as the ways in which these needs are being met and might be met by the enterprise of interest and others. This also includes knowledge of social, economic, and industry/market factors and trends. A typical goal is to increase the coverage and decrease the uncertainty of market needs.

- **Technology Base (TB):** The knowledge and skills that enable potential creation of solutions to satisfy current and likely future market needs, including both product and process knowledge and skills. It can be embodied in off-the-shelf technologies, archived knowledge, and technical staff members. A typical goal is to increase the knowledge and skills of an enterprise.

These four assets of an enterprise interact in important ways. For example, strong CB but weak PB results in eventual dilution of CB. As another example, strong TB can, with some delay, improve weak PB, but this will only pay off if either MB or CB is strong. In general, there needs to be balance among these four assets.

Fig. 8 depicts an overall investment model [62] that illustrates how these four assets interact. The ovals indicate the four assets. The other elements of this figure represent the activities that contribute to creation of the four assets. (Note that the CB serves as a surrogate for traditional private-sector financial returns. This enables also using this model to represent constituencies of public sector, nonprofit, and other types of enterprises.)

This model can be used to frame a range of essential tradeoffs that all enterprises face when contemplating R&D/technology investments. In particular, all of the activities in Fig. 8 compete for resources. Investments in R&D/technology mean fewer resources, at least on the short term, for marketing and sales, manufacturing, etc.

However, minimizing investments in R&D/technology eventually undermines TB, which either undermines PB or, at the very least, results in products that rely on other enterprises’ intellectual property. The extent of this tradeoff obviously depends on company/market/industry-specific relationships in Fig. 8.

While there is no general answer regarding the best resolution of this tradeoff, it is clear that enterprises should focus on creating balance among these four key assets. The common denominator among these assets is information, ranging from what customers need to who they are to how to meet these needs. Creating balance among these assets involves understanding how these information elements interact over the time horizon of interest. This is a difficult task, but nevertheless the essence of the problem.

VI. CONCLUSIONS—PUTTING TECHNOLOGY TO WORK

This article has summarized and integrated the state of knowledge of R&D/technology management. The goal was to clarify what we know and discuss how we can leverage this knowledge. Our overall conclusion is that understanding at multiple levels is key to deeply understanding R&D/technology management. Further, these multiple levels of understanding can be integrated by considering information access and utilization throughout these processes.

This understanding is crucial during these times of disaffection with the “faith model” of R&D/technology investment. Those with resources now want to know that creation of knowledge and technologies will be managed to assure returns on investments. While such management can certainly be improved, the nature of technological innovation precludes eliminating uncertainty from this process.

The key, therefore, is understanding how to cope with substantial uncertainties and recognize when opportunities are truly at hand. This requires that investments be patiently nurtured and prudently monitored. Predicting the unpredictable is not possible. However, recognizing that the
unpredictable—and highly valuable—has happened is a central skill in putting technology to work.

REFERENCES


William B. Rouse (M’72–SM’78–F’85), for a photograph and biography, see p. 316 of the August 1998 issue of this Transactions.

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