RESEARCH AND DEVELOPMENT MANAGEMENT

1. Introduction

Over the past several decades, output from research and development (R&D) activities has become increasingly critical to the economic and social welfare of nations. The global importance of modern R&D is reflected, now, by:

- How much money is being spent on R&D by nations (the amounts are generally stated as percentage of gross domestic product [GDP], in fact)
- How much money is being spent on R&D by businesses, particularly high-technology businesses (some individual companies spend enough on R&D to be accounted as a percentage of GDP)
- How many people are being employed in R&D
- How much data are being generated by R&D
- How fast the knowledge and technical (science and technology) frontiers are moving.

For a leader of R&D, the stakes are high and the role is visible beyond the confines of the institution. For scientists and engineers, remaining abreast of advances in knowledge and in techniques is an enormous challenge. For both leader and staff, new information management strategies and tools are no longer marginal to R&D effectiveness; they are central.

In addition to these factors, the macro-environment in which R&D takes place is turbulent. That is, the rate of change in the science and technology system is rapid; the magnitude of change is large; and the unpredictability of change is high. The macro-environment is also complex; the context in which R&D occurs is hard to understand. Uncertainty arises not only from science and technology discoveries (unexpected breakthroughs as well as failures) but also from geopolitical shifts and even natural catastrophes.

The task of designing technology strategy, whether in the public or private sector, is growing both more difficult and more crucial to the success of the institution as well as the nation. The role of R&D leader is demanding to the extreme: new ways of thinking, new approaches to managing information, and new frameworks for devising strategy are only a few of the demands on the leader today.

Yet, even in the face of a long (and growing) list of external challenges, one must never lose sight of what is truly paramount. At the end of the day, no matter how large the R&D budget or how large the institution in which these activities take place, it is *people* who generate the ideas in an *organization* that helps or hinders the process of innovation. Economic, societal, and institutional challenges must never distract the leader's attention from providing the motivation and support needed by individuals. Effective leadership of R&D is all the more of significance because it is likely to be overshadowed by the sheer size, cost, and complexity of the system in which it occurs.

The external factors and their challenges for modern R&D are addressed in this article. But, the perspective is that the factors and challenges are less important than their impact on people and organizations.

2. Research and Development Context: The Global Science and Technology System

In the Frascati Manual, prepared for the Organization for Economic Cooperation and Development (OECD), research and development are defined as:

…creative work undertaken on a systematic basis in order to increase the stock of knowledge… and the use of this stock of knowledge to devise new applications (1).

The OECD encompasses 30 nations with a stated mission of working "together to address the economic, social and governance challenges of globalization as well as to exploit its opportunities."

R&D actually comprises three activities (again from OECD definitions):

1. Basic research ("undertaken primarily to acquire new knowledge… without any particular application or use in view"),
2. Applied research ("original investigation… directed primarily towards a specific practical aim or objective"), and
3. Experimental development ("systematic work, drawing on existing knowledge… directed to producing new materials, products or devices, to installing new processes, systems and services, or to improving substantially those already produced or installed") (2).

All R&D efforts like the above, whether conducted in a small university or in a large industrial firm, take place in the context of the global science and technology (S&T) system. Like all systems, this encompasses myriad interconnections among the component parts, such as the "invisible colleges" of scientists, who meet regularly at international conferences (3). And, because the component parts are interdependent, a change in one part of the system produces changes in other parts (4). For example, a sizable increase in public funding of U.S. biomedical research universities is likely to produce an increase in potential innovations that attract global venture capital. On the other hand, a sizable increase in funding of biomedical science may contribute to a decline in student applications to U.S. graduate engineering programs.

Understanding that modern R&D takes place in this context is important for two reasons. First, "the products of science and technology underpin modern economies" (5). National economies benefit from and depend on crucial high-technology industries and services defined by "their high R&D spending and performance, and which produce innovations that spill over into other economic sectors" (6). Most of these industries, in turn, depend on academic research that enables advances in the private sector, as noted above. When the output of research is high-quality innovation, those firms investing in R&D enjoy positive economic returns. At the same time, society benefits. In fact, "[r]eturns to society overall are estimated to be even higher. Society often gains more from successful scientific advancements than does the organization conducting the research" (6).

The second reason why it is important to understand modern R&D in context is that the global S&T system can be characterized by certain dynamics that affect the *people* and *organizations* involved in R&D.

2.1. Increasing National R&D Expenditures. In so-called industrial nations, the amount spent on R&D "is a key indicator of government and private sector efforts to obtain competitive advantage in science and technology" (2). Essentially since World War II, expenditures on R&D have increased steadily, until the OECD average in 2001 was more than 2% of the 30-member-nation total gross domestic product (GDP). Since 2000, government spending on R&D in the OECD has grown an average of 3.5% in real terms.

Of course, certain nations spend more on R&D, such as the United States and Japan. Growth in real dollars has been about 6% per year in Japan and 7% in the U.S. (compared with less than 2% per year for the EU25, ie, 25 nations in the European Union) since 1995. But, between 2001 and 2004, R&D intensity (R&D divided by GDP) increased steadily throughout all OECD regions.

One outcome of an increase in R&D spending has been to move nations towards a *knowledge-based economy*. Nations differ in the relative contributions of manufacturing, services, and agriculture (sectors of the economy) to GDP. In nations that spend a sizable amount on R&D, their knowledge-based services, such as information technology and health care, now contribute the largest value-added to their economies. Since 1990, there has been a steady rise in knowledge-based services in most of the OECD nations. By 2002, all services (including knowledge-based ones) accounted for nearly three-quarters of value added in the OECD, while manufacturing accounted for less than 20%. On the other hand, high-technology manufacturing (industries that expend a large proportion of sales on R&D, such as biopharmaceuticals) accounted for almost 8% of that 20%.

Increasing expenditures on R&D are reflected in increasing numbers of people employed in R&D. Between 1995 and 2003, the average annual growth rate of this area of employment has been nearly 3% (OECD, 1995–2000). Researchers, primarily scientists engaged in the three types of activities defined earlier, have increased even faster. In the U.S., that category grew by nearly 5%; in Japan, by more than 4% over that period.

2.2. Increasing Health R&D Expenditures. Although defense expenditures on R&D account for both the larger amount and larger percentage of GDP in a number of nations, health R&D generally comes second. "R&D expenditures on health are of great interest because of the sector's size [within overall services] and expected growth as the population ages" (2). Often, a large proportion of health R&D is accounted for by the biopharmaceutical industry (a high-technology industry). In the UK, for example, the latter industry R&D accounted for more than 20% of all business R&D and for more than 0.3% of GDP in 2002.

Again, the U.S. accounts for the largest investment in health R&D: 0.25% of GDP in 2004 (when GDP was nearly $12 trillion), versus the OECD average of 0.1% of GDP. In fact, the U.S. really supports the rest of the world by means of its biomedical R&D, accounting for about three-quarters of all health R&D in the OECD nations. Between 1994 and 2003, support of biomedical research doubled (in constant dollars). Of that total, private industry accounted for 57%; the National Institutes of Health (NIH) accounted for 28% (7). Most public funding of R&D in universities in the U.S. is allocated to the medical and biological sciences (85% of reported R&D) (8).

2.3. Increasing Business R&D Expenditures. As to who conducts R&D, businesses far outweigh other enterprises for "the bulk of R&D activity in OECD countries in terms of both performance and funding [accounting for] close to 68% of total R&D" (2). This, too, has increased steadily for the past two decades. Business R&D intensity (R&D spending divided by the domestic product of the industrial sector) increased from the mid-1990s to 2000; it now (2003 or later) averages about 2% in the OECD regions, more than 2.5% in the U.S., and more than 3% in Japan.

2.4. Overwhelming Growth of Data. It is not at all surprising that, with such steady increases in funding of R&D, scientific and technologic data have grown explosively. A report from the U.S. Office of Naval Research stated:

> Over the past decade, with the growth and expansion of electronic storage media, there has been a virtual explosion of multimedia data readily available. In particular, the use of CD-ROMs and the Internet has provided overwhelming data resources to the user community.... The Web version of the Science Citation Index (SCI) accesses over 32 million technical documents from 5600 technical journals, and presents this information in semi-structured textual format. In 2004, the SCI added approximately 1.1 million new technical documents (9).

This volume of articles, according to the OECD, "is a key indicator of the output of scientific research" (2). Like the other indicators, though, most of the article output is accounted for by a few nations, particularly the U.S. (the geographical leader), and is correlated with R&D expenditures. Still, the past decade has witnessed an increase in article output intensity in most OECD countries.

The explosion of data by means of articles, notes, and reviews published (and accessed via SCI, as above) is one output from R&D; the others are trained personnel, advances in knowledge, and patents. Yet, because of the link between publication and, especially in academia, career advancement, simple counts may distort "the relationship between real output and publication-based indicators... [as well as] quality" (2). That is why citation is an important index. In terms of articles cited, ie, not just articles published, the U.S. and Switzerland account for the largest numbers. As the OCED FactBook notes, both countries "have a strong reputation worldwide in biomedical research and physics" (2).

2.5. Challenges Facing Leaders. Even such a cursory overview of these dynamics highlights a number of the challenges faced by leaders of R&D, whether in public or private sector, in large or small organizations:

Much is at stake. If science and technology provide a crucial foundation for modern economies, then managing R&D effectively has consequences beyond the individual institution in which it occurs.

Management is very visible. Because so much is at stake—both the enormous amount of resources devoted to R&D and the potential benefit to society from its products—modern R&D and its leadership are subjected to more, as well as more visible, scrutiny.

The frontiers of science and technology are broad and fast-moving. There is, of course, no simple, direct correlation between amount of resources devoted to R&D and speed of discoveries from R&D. Putting a thousand or ten thousand scientists on a project to find a cure for cancer does not guarantee that a cure will be found. Difficult scientific problems still require the innovative thinking of individual minds. But, with so many researchers engaged in work globally, and with the modern communication infrastructure supporting them, the S&T frontier grows wider and faster. Overwhelming data resources to the user community allow a critical mass of intellectual expertise to be devoted to a problem more rapidly than ever before. In this faster-moving, rapidly changing environment, R&D leaders must move quickly, decisively, and intelligently from selected ideas to developing the innovations.

Information overload is inescapable. Explosive growth of data and systems to transport it also produce cognitive overload. Most individuals are all too aware of proliferating emails. Imagine the situation faced by scientists, who want to stay connected electronically to a global system that produces about 1 million new documents annually. Using hydraulics imagery, that is a flow too strong to be managed by traditional pipes and valves. No one person can master the information. The days of the lone investigator or single R&D leader making most decisions are past. In R&D, leaders must determine explicitly the types of decisions they will make and the types of decisions they will delegate to qualified subordinates. As the science frontiers advance, R&D leaders must examine their choice continuously and as dispassionately as possible.

Although important to recognize and to develop strategies for dealing with, these societal and institutional challenges must never distract leaders' attention from the most crucial element in R&D. That element consists of the individuals who work at the bench and in the library, and it is their motivation and support that must remain paramount in leaders' efforts. If effective management of R&D has always been important, it is even more critical today, because it is likely to be overshadowed by the sheer size, cost, and complexity of the system in which it occurs. It is for this very reason that the focus is on the people and organizational issues in modern research and development. At the end of the day, no matter how large the institution or how sizable the budget, it is *people* who generate the ideas in an *organization* that helps or hinders the process of innovation. The latter process, in turn, determines the success or failure of projects and the output that benefits nations.

3. Turbulence and Complexity

Several key dynamics characterize the global S&T system or context in which R&D takes place. This system, in turn, is a component of all that is considered external to an organization and is termed the *environment*. As has become very clear over the past several decades, that environment is neither stable, simple, nor predictable. It is turbulent because its components are (to varying degrees) themselves turbulent, and it is complex.

3.1. Turbulence. *Turbulence* describes a condition in which (*1*) the rate of change is rapid, (*2*) the magnitude of change is large, and (*3*) the unpredictability of change is high. The description was applied to the social as opposed to physical sciences by Emery and Trist (10) and later to the environment of modern industries by Ansoff (11). In former times, when the environment could be described as simple, stable, and certain, the model of "planning" was appropriate. The word, *plan*, comes from the Latin for "level ground" and implies that leaders can, essentially see ahead (ie, into the future with some certainty). When the condition of turbulence applies, however, more sophisticated management tools are needed (12). Similarly, under conditions of turbulence, more sophisticated leadership of R&D is needed (13).

Biomedical Science and Technology. The sizable and growing resources allocated to health/biomedical R&D, described in Section 2.2, are less the cause than the outcome of truly transformative changes in the underlying disciplines. Consider that, from the beginning of the twentieth century to about the mid-1970s, organized biomedical science consisted essentially of scientists (in academia, government, and industry) working alone or in small teams in their laboratories, with government acting as primary source of funds for public sector research. During much of that time, in comparison with efforts in the physical sciences, biological science was considered "small" science (3). Biological technology was, similarly, small technology (eg, utilizing microscopes and test tubes, which are quite small in comparison with, say, the huge instruments employed in Los Alamos atomic energy research).

But, in the mid-1970s, discoveries in the disciplines of molecular biology and what is now known as biotechnology completely altered R&D. Compared with the rate of progress of nearly the past century, it was as if biomedical science changed in the blink of an eye. Revolutionary, discontinuous discoveries triggered a rapidly advancing knowledge frontier. Like a wave, insights gained about one phenomenon cascaded into other areas. Questions that may have been asked earlier but remained unanswered or only partially answered were now illuminated. In just a few decades, biological processes, such as the role of prostaglandins in inflammation and mevalonic acid in cholesterol metabolism, became better understood. Even the structure of DNA itself was deciphered. A number of complex biological processes could now be described by simple chemical reactions.

The feedback loops between science and technology and between invention and innovation were dramatically shortened. Medicinal chemistry had been the technology of drug discovery since Ehrlich collaborated with Fabwerke Hoechst in the late 1800s. Almost 100 years later, this chronology and these events occurred: In 1973, Herbert Boyer of the University of California at San Francisco and Stanley Cohen of Stanford discovered how to introduce a piece of DNA from one organism to another (rDNA). In 1976, Boyer and Robert Swanson, a venture capitalist, created a company called *Genentech*. Only five years after Boyer and

Cohen's academic work, recombinant human insulin was created. Shortly thereafter, *Humulin* was marketed by Genentech.

One consequence of rapidly advancing science and technology frontiers is the compression of product and process life cycles. For example, the sciences underlying the biomedical product, the R&D technologies used to discover the product, and the process technologies used to prepare and develop that product can become outdated quickly by new discoveries. Also, how work is accomplished is vastly different today from even a decade earlier. Computer programs that can model complex molecular structures and new combinatorial chemistry techniques allow drugs to be "designed" to fit specific receptors, instead of randomly found by screening. Human receptors can be cloned as targets for new drugs. Libraries of molecular structures more accurately elucidated by nmr and mass spectroscopy are available to scientists. As discussed in Section 2.4, the Internet allows members of "invisible colleges" to communicate immediately and continually if desired. Finally, the area of nanotechnology is expected to produce the next set of transformative changes across many fields of science and technology, including biomedicine.

In summary, the rate of change in biomedical science and technology is rapid (eg, rDNA to Humulin in a few years); the magnitude of change is large (eg, from a handful to thousands of biotechnology companies); and the unpredictability of change is high. Similar illustrations can be found in nearly all branches of science and technology.

Some Implications of Turbulence. There have been extraordinary increases in the speed with which information is exchanged among scientists globally (ie, the rate of change is rapid). Because science builds on work that has gone before, knowing about this prior work quickly is important. Scientists can communicate instantly, although some readers may remember when one had to reserve a trans-Atlantic telephone line well in advance, in order to speak with someone overseas. One implication of turbulence for people and organizations is that competition in research, always a factor, is now global competition and in real time. Publications, lectures, proceedings from symposia are now online, which allows scientific rivals to find out about results and so forth almost immediately.

Because of both global competition in research and the compression of product and process life cycles (ie, the magnitude of change is large), outsourcing research tasks often to less expensive areas of the globe is becoming common. This has a number of implications for people and organizations:

- Scientists whose jobs are outsourced have their career paths impacted and may become unemployed.
- If tasks are outsourced, there is a definite loss of core competencies (discussed in Section 5). R&D leaders must consider their assumption that *any* smart person can do a given job. When are in-house experience and seasoned judgment valuable and not to be jeopardized by outsourcing?
- At the organizational level, outsourcing results in loss of "institutional memory." Again, R&D leaders must ask: What might be the long-term

effect of losing in-house expertise? Some have even compared the process of outsourcing as replacing internal experts with mercenaries.

- The magnitude and rate of flow of information now requires R&D leaders to select (in advance) the general decisions they will make and those they will delegate. If tasks are outsourced, then leaders will also confront the question of where the myriad research judgments and prioritization decisions will be made. If the answer is, essentially, at a remote site and by a stranger (who does not have the perspective of the internal expert), then the outsourcing decision itself should be subjected to extensive examination.

3.2. Complexity. Complexity, by definition, is that which is hard to understand fully. The macro-environment of R&D is truly complex. Some of the reasons were alluded to in Section 2 and include the following. First, competition occurs globally and in ever more fragmented markets. Thus, a greater array of inputs from many different disciplines, sources, and locations must be brought together, to develop new products, processes, services, and applications.

Second, R&D must also support (in the private sector) manufacturing and markets, as well as in general deal with environmental concerns and respond to the rapidly moving science and technology frontiers.

Third, as the OECD data illustrate, most R&D is conducted by organizations in the U.S., Japan, and Europe. But, other powers are emerging from India, China, the Asia-Pacific region, and Eastern Europe unless these countries are disrupted by geopolitical forces as well as natural disasters (14). Geographically dispersed R&D, whether because of outsourcing or because of setting up satellite facilities, requires leaders who can manage far-flung, complex, interorganizational relationships, and new organizational forms. These may involve licensing, joint ventures, strategic alliances, collaborative agreements, consortia, incubators, mergers, and acquisitions.

Fourth, and not addressed in the earlier discussions, the social support and political will for extending resources to science and technology (and, thence, to R&D) depends on a country's ability to assess and balance risks and benefits and to put these in perspective with other societal needs. The leader of R&D must realize that certain societal concerns can make specific new technologies (eg, genetic engineering), products (eg, genetically modified foods), or processes (eg, stem cell research) unacceptable.

3.3. More Implications of Turbulence and Complexity. R&D takes place in the context of a global science and technology system, which in turn is a turbulent and complex component of the macro-environment. Added to the challenges described in Sections 2.5 and 3.1 are the following.

Impact on People.

New tools, advanced techniques, and the rapidly increasing knowledge base required to do one's job today put added stress on scientists at every level in R&D. The challenge to keep up with new technologies is increasingly difficult (if not impossible) for individuals.

There are also multiple pressures placed on leaders of R&D: there is not a limitless amount of money to finance research; there are priorities that need to be set among scientific projects; they are in a competitive situation where time, money, and the effectiveness of research are all important to the viability of the organization (university, government, and for-profit).

The leader of R&D must effectively manage a balanced portfolio of projects, scientific approaches (high risk and lower risk), and development candidates that will deliver new products in a regular fashion, without smothering creativity at the bench level.

There must be the right environment in the organization for people to discover and for individuals to think, explore, and experiment freely. That freedom must be weighed against organizational goals, priorities, and timelines. New proprietary information, the product of discovery, may have to be protected for the viability of the organization; yet, scientists want to disseminate quickly what they have found. Goals of scientists and goals of organizations may differ. The R&D leader must strive to satisfy both without seriously compromising either.

Impact on Organizations.

Company and individual strengths and core competencies must be created, clearly identified, leveraged, and protected. In-house expertise is a major competitive advantage. Corporate, divisional, and project goals (short and long term) must be clearly thought out, coordinated, and explained to all workers.

Increasing competition within industry (affecting both the organization and the individual scientists) from a “flattening world” must be recognized. The “new era of globalization is about the emergence of completely new social, political, and business models” (14).

A flattening world is also characterized by increased outsourcing of work, as many companies “are also now going offshore for services such as software and chemistry” (15).

Effective information exchange between downstream functions in a company (eg, manufacturing, marketing) and the upstream research function is vital to developing common goals and timelines, despite the unpredictable nature of discovery. The most efficient path to project success will involve the input of all functions, usually by means of interdisciplinary teams who appreciate the challenges and problems faced by each other. As projects become global efforts, the challenges increase. What functions, and what people, should be involved? Who needs to know what, and by when?

By necessity, organizational goals must be aligned with research goals; they must be realistic; and, they will change over time. There are limited financial resources in both public and private institutions, and some projects will not be funded, depending on the likelihood of their success. That success, in turn, is determined by the usefulness of existing knowledge and the innovative thinking of the scientist.

4. People

4.1. The Education of Scientists. What are scientists? Who they are in terms of their education and training (16)?

Essentially, scientists are individuals with a terminal degree (doctorate) in a discipline such as chemistry, or in medicine, or in engineering, and so on, who have characteristic thinking patterns that can be described as: (*1*) analytical, orderly, and building on existing knowledge; (*2*) clear, rational in achieving goals and solving problems; (*3*) data-driven ("show me the data"); and (*4*) capable of separating fact from opinion (their and others').

Scientists spend years in a narrow discipline, undergoing a lengthy, intense, and particularly designed education and socialization (17). Students may begin a doctoral program immediately after their baccalaureate degree, and, after finishing, enter a postdoctoral period of further specialization for one to several years. During this time, their progress and rewards are based on individual, intellectual accomplishments: solving technical problems, crafting hypotheses to explain new phenomena, devising bench experiments to test hypotheses, carrying out suitable experiments, and interpreting the results. So, although they may be guided by a mentor, work in groups, and conduct experiments with colleagues, they are recognized for their own ideas and receive individual grades and individual degrees.

Because of their very specialized education and training, scientists are narrowly trained professionals who are likely to display two qualities. First, they will value individual accomplishments. Second, they are usually skeptical of management sciences (eg, leadership, organization strategy, and so on). To scientists, at least initially, true science is hard science: observable, measurable, replicable, and nomothetic, such as is seen in chemistry, mathematics, or physics. Although even quantitative management disciplines like finance and accounting may be questioned as being hard sciences, behavioral and managerial theories are often of highly suspect credibility. "The idea of management as a professional skill with its own disciplines can be a tough sell. New training has much to overcome in the way of old prejudices" (18).

4.2. Critical Roles in R&D. Once scientists complete their academic education and training, they enter the workforce, where they encounter the necessity of fulfilling roles other than those of scientist, or researcher, or engineer, etc. A role is a function assumed by an individual for a purpose. The nature of work, what a person does; what methods, techniques, tools are used; and what is produced, determines the relevant roles and role sets that are assumed by an individual for a particular situation.

With regard to science and technology innovation, prior studies have found certain roles to be critical to performance. That is, the better individuals are at fulfilling these roles, the higher the caliber of the output and the more successful the project:

"*Idea generating*. Analyzing and/or synthesizing information from which an idea is generated for a new technical approach or procedure or a solution to a challenging technical problem.

Entrepreneuring or championing. Recognizing, proposing a new (his or her own or someone else's) technical idea, approach or procedure for formal management approval.

Project leading. Planning and coordinating the diverse sets of activities and people involved in moving a demonstrated idea into practice.

Gatekeeping. Collecting and channeling information about important changes in the internal and external environments.

Sponsoring or coaching. Behind-the-scene support-generating function of the protector and advocate" (19).

In addition, the studies found that:

> [Each] role is different or unique, demanding different skills [and] each role tends to be carried out primarily by relatively few individuals, thereby making even more unique the critical role players. Some individuals fulfill multiple critical roles concurrently or in different stages of the same project. But even more people are likely to contribute critically but differently at different stages of their career (19).

Another important role that scientists must fill is *boundary spanning*. This entails extending project communication across research sites, across different disciplines, across different functions, across different parts of the organization, and so on. Each constituent group on one side of a boundary is likely to share a common language (terms, acronyms, and idiosyncratic connotations of the vernacular), because they share a common experience and perform similar tasks. To accomplish the boundary spanning role effectively, the individual must possess the competency of a "multilingual translator, fluent in the language of customers, engineers, [and the] translator between customer experience/requirements and engineering specifications" (20). The boundary spanner must interpret the information provided by one constituent so that it is understandable by another and be able to communicate across the so-called language barriers that separate constituents.

Accompanying boundary spanning is the linked role of *boundary managing*, which entails managing the organizational boundary between the project and all the other constituencies. Other research on science and technology innovation found that "the ways teams managed their boundaries were strongly related to their performance: ...As studies of boundary spanning roles have shown, effective teams do not rely on extensive external communication by all members, but instead have individuals (gatekeepers or liaisons) who collect, interpret, and triage information from sources outside the team or organization. [Such] external communication must be carefully managed to ensure that effective boundary tasks are accomplished" (21).

To accomplish the boundary managing role effectively, the individual must possess the competencies of an ambassador "representing the teams to others and protecting the team from outside interference"; a task coordinator "coordinating and negotiating with other groups"; and a scout "general scanning for ideas and information and building a general awareness and knowledge base" (21).

4.3. The Climate for Creativity. Understanding some of the consequences of scientific education and training (eg, lack of familiarity with teamwork skills) and ensuring that the right roles for innovation are filled are necessary but insufficient criteria for creativity. Creativity in R&D is not programmable, that is, it cannot be guaranteed by certain factors. Also creativity is affected to a very large degree by the leader. In fact, probably the most important responsibility of the leader of R&D is to provide and maintain the *right* climate, because scientists will then be enthusiastic, energetic, and more likely creative.

The right climate is one that supports and maintains positive motivation. When scientists are positively motivated, there is little they cannot accomplish. If they encounter resource constraints, they will find other means. If they encounter a seemingly intractable problem, they will keep turning the problem on its head and persist until they find a solution.

Behavioral science research has found that the foundation for developing a motivated group includes the following (22):

Reasonable working conditions. Safety in the laboratory must be ensured; space must be at least adequate and decently appointed; the required (ie, most modern) equipment must be available to do the job, and so forth.

Competent people. People trained appropriately for their job.

Assurance of the link between effort and outcomes. People must believe that their effort will lead to the desired job performance (eg, discovering the genetic component of a disease); they must believe that this performance will lead to certain outcomes (eg, project success and personal recognition by their scientific peers); and they must value those outcomes.

Equity and fairness. People must be treated and paid fairly in the organization, as compared with similar organizations.

Appropriate challenge. People should not be asked to perform the impossible, but they should be encouraged to go beyond what they initially see as their limits.

As one might imagine, given the education and training of scientists described above, other factors must be carefully addressed by the leader of R&D. A number of studies have revealed remarkably consistent responses to questions of what inhibits creativity and, by opposition, what supports it (23). For example, creative people do their work because it is inherently interesting, enjoyable, and satisfying. They do not respond to such extrinsic motivators as management pressure, project evaluations, or competition for rewards.

The right climate is also one in which scientists are buffered from *inappropriate* pressures (eg, preparing too-frequent written reports). The leader of R&D must understand that, because scientific activity often appears to outsiders (such as top management) to be “slow, risky, and full of intermediate failure”, they must shield their scientists from the “powerful process-avoiding and process-terminating forces brought into play by uncertainty, fear of failure, intolerance of ambiguity, and pressures for quick and certain results” (22).

4.4. Hallmarks of a Good Leader of R&D. Who are good leaders of R&D? And, aside from the impact on creativity, why is effective leadership important?

In terms of the latter question, a study of U.S. National Aeronautics and Space Administration (NASA) scientists concluded:

> [It] is no longer enough to be excellent in [one's] scientific discipline. A research leader needs to get work done with and through other people. Time, money, morale, and quality of product are only a few of the elements that are at risk when ineffective leaders are at the helm (24).

A long-term, descriptive and exploratory study of how scientists themselves define effective leadership and experience a good leader of R&D (25) indicate that effective leaders are described as:

- Caring and compassionate
- Possessing managerial skills (communicating effectively and listening well, resolving conflict, being organized, holding informative meetings)
- Technically accomplished to lead a scientific effort
- Being a good role model.

The importance of the leaders' care and compassion to people working in the laboratory is striking. The best leaders are characterized as "scientifically very competent, and compassionate and caring deeply for collaborators and subordinates".

Leaders who are "highly enthusiastic and support others' unorthodox ways of thinking" create an atmosphere in which professional growth and scientific innovation seem to occur naturally. An effective leader "can get the best out of each person"; ensures that each person "feels a part of what is happening and wants to do a good job"; and has "the ability to inspire and make everyone enthusiastic about the research". These leaders generate "a fun and productive atmosphere in which each person can thrive in his/her own individual way; they support a stimulating environment", they encourage ingenuity; and are able to appreciate innovative/novel/different ideas. Scientists working for an effective leader are enthusiastic, energetic, and committed. All of these qualities are likely to be associated with high caliber, creative output.

4.5. Need for Additional Training. Remember that the training of scientists is likely to produce solo contributors; ie, people who have been assessed and rewarded for individual accomplishments, and management skeptics. But, most scientists will at least supervise a small group of people and all scientists in the workforce (in academic institutions or private companies) must take on organizational roles. Leadership training should be available, even required, in graduate and post-graduate scientific education. At the very least, scientists should be trained in basic supervisory skills.

Beyond basic supervisory skills, scientists who want to take on more managerial responsibilities must be provided with comparatively more sophisticated education and training. First, though, they should be helped to reflect seriously on their temperamental suitability and reasons for moving to wider scope of leadership. Not every supervisor of a small group can become an effective leader of R&D. Given suitable talent for taking on greater leadership responsibilities, and with appropriate management education and training, scientists can be helped to lead R&D effectively. As with all competencies, of course, their skills in leadership must be assessed regularly, becoming an integral part of ongoing performance reviews.

5. Organizations

Under existing, and likely future, conditions of turbulence and complexity, leaders of R&D require new frameworks, new ways of thinking, and new approaches to managing the organizations in which work is conducted. One of the most important organizational-level aspects of their role is to design a technology strategy that will support corporate or institutional strategy (26).

5.1. Technology Strategy. There is too often a gap between scientists' understanding of corporate or organizational strategy and its implications for R&D, and the understanding by nonscientists of the impact of R&D decisions on the achievement (or not) of strategic objectives. One reason for this gap is that people at the institutional leadership, R&D, program, and project levels in the organization may have incomplete or even contradictory perspectives of the role of science and technology in the attainment of objectives. Another reason is that communication may be primarily top-down, or it is impeded because people speak different "languages" (eg, *business* versus *science*) and are rewarded for achieving different goals. Whatever the cause, the result is the same: internal consistency among institutional, R&D, program, and project decisions is missing.

If the macro-environment were simple, stable, and predictable, the above inconsistency might be tolerated. However, degrees of strategic freedom in science and technology organizations have been reduced by (among others):

- Cost-constraining pressures from buyers, coupled with social and political demand that new products and services demonstrate clear advantages over current ones (cf/ Section 3.2).
- Compression of product and process life cycles by rapidly advancing science frontiers (cf/ Section 2.5).
- Intense competition; thus, astute research decisions and speed of development are even more crucial (cf/ Section 3.3).

Because of the above, any gap, any inconsistency or lack of coherence between business and technology decisions is truly perilous.

In order to close this gap there must be a change in the way scientist and non-scientist think about strategy, environment, and technology. R&D leaders should reframe their strategic task from one of planning to one of defining a technology *trajectory*. Such reframing replaces planning algorithms with heuristics and images, such as energy source, speed, coordinates, space, which are far more suited to a future likely to contain surprises, perhaps hostile forces impinging on the organization, and myriad possibilities.

When R&D leaders reframe science and technology efforts as contributing to an overall trajectory, then every discovery program and every project can be viewed as a vector. The sum of these individual vectors is the R&D vector at a point in time, and the technology trajectory is the metaphoric path the vector takes over a period of years.

The necessity for a different perspective on strategy is dictated by the turbulence and complexity of the macro-environment. Within this new perspective, the most uncertain work of the organization, research and development, becomes central to the strategic process. Programs and projects become viewed as booster rockets, providing energy and keeping the institutional and technology trajectories aligned. Technology strategy sets the context for decisions about types of programs and projects to be funded, and how; their priority ranking within the portfolio; and the criteria to be used in making tradeoffs. It determines science and technology objectives, core technologies (see below) in which the firm will be proficient, general technologies that will support R&D, and so on. Based on these decisions, science and technology resources—people, time, facilities, equipment, and money—can be allocated to discovery programs and development projects. At the same time, events occurring at the program and project level, such as scientific and technological break-throughs, or dead ends, or new information about competitors' activities, quickly inform the strategy. Tactics to increase, to decrease, or to shift personnel and funding can be implemented proactively instead of after-the-fact.

As should be evident, effective alignment of strategic trajectories, and enhancement of technology strategy, demands an intense feedback loop of two-way communication among all spheres of management: corporate, research, development, program, and project. Strategy is, literally, "embedded in projects;" thus, institutional, R&D, program, and project decisions are inextricably linked (27).

Of course, science and technology resources are not just used in R&D. The organization's scientific and technologic capacity must continually be developed. As the frontiers of science and technology advance, the intellectual capability of R&D must advance as well, by incorporating new technologies, by training and skills improvement of current staff, and by recruiting and hiring new staff. Competitive technology strategy demands another feedback loop between science and technology *use* and science and technology *advancement*. Table 1 summarizes the relevant spheres of action in this reframing.

5.2. Strategic Consistency and Organizational Competitiveness. Strategic consistency does not imply either homogeneity or lack of difference. There must be a climate of challenge as well as sufficient intellectual diversity within R&D, if the output is to be innovative (28). In such a climate, there are bound to be differences of opinion. Consistency, instead, connotes harmony and agreement between the technology strategy and the strategic vision, which must be widely shared and adhered to throughout the organization. Vision is the metaphoric endpoint of institutional and technology trajectories and describes (among others) the desired:

- *Competitive position*: to be among the top five organizations in a particular sector; or to be number one in a niche, etc.
- *Geographic scope*: to be global, international, etc.
- *Treatment of constituents*: to be impeccably fair; to exceed external standards of quality; to contribute in a genuine way to communities in which the firm is located, etc.
- *Technology identity*: the orientation towards science and technology that will characterize overall R&D (such as defining the leading edge).

Given that consistency, then science and technology resources must be allocated appropriately. To be competitive (or to remain viable) under conditions of turbulence and complexity, the most important of those resources are the knowledge, skills, and capabilities of people within R&D (and other infrastructure functions). Investment in people means more than head count, because the most important investment is what goes <u>into</u> the head (count), to enhance organizational innovation. Highly trained specialists, with relevant practical experience, are vital to the organization's success.

For example, suppose that the R&D leader in a startup firm wanted to define the leading edge of the relevant sciences and technologies. The technology strategy would require investment in both internal salaries and support for activities that would ensure their scientists could define the leading edge, such as: collaborative efforts with public sector researchers connected to knowledge networks expected to define the leading edge; travel to and/or short sabbaticals in facilities in which unusual technologies are employed, to expose scientists to a wider range of possibilities from the technological network; cross-training and rotation to other areas of the firm, to discourage "silo" formation and narrowness of outlook.

These activities, and all organizational assistance needed (such as process consultation to foster challenge and foment within R&D), would ensure that the "head count" resource provided a true competitive advantage.

Finally, even before business objectives are agreed upon, there must be candid and intense discussions among institutional, R&D, and other functional managers about the implications of these objectives for short- and long-term science and technology resource allocation. There will be times when a business objective, such as target profitability, cannot be achieved if sufficient resources are to be invested in R&D. Because meeting profitability targets brings rewards to senior leaders <u>now</u> but investing in R&D brings rewards years later, there is constant tension in the trajectory-alignment process. Business and technology trajectories must be aligned (ie, internally consistent) over the long term. But, aligning them will always involve short-term coordinate adjustments to the business vector and/or the R&D vector.

5.3. Core Technologies. Although every science and technology organization makes use of multiple technologies in R&D, not all of these are *core technologies*. Core technologies have been defined as those that should be most protected from external influences. They should be kept and/or developed in-house as much as possible, so as to reduce "the influence of the environment on the technological core" (29).

The term, *core technology*, should be distinguished from that of *core competence*. A core competence can include, but is not limited to, a technology. Competence of organizations can encompass culture and values, as well as knowledge and expertise (30). A core technology is more narrowly defined as discipline knowledge and expertise. Such technologies will have the following characteristics:

- *They represent a sizable amount of tacit knowledge within the organization*. There are no externally published instructions that have yet captured what R&D scientists are capable of accomplishing.
- *Their software is more important than their hardware*. There may be little in the way of tools or equipment. But, even if there is a sizable component of equipment, its use has not yet been mastered outside the organization.
- *They are very close to the respective leading-edge knowledge and science frontiers*. It is likely that R&D scientists are working intently with public sector researchers or researchers outside the particular sector or industry.

Core technologies are a matter of strategic choice. Examples could include assay as well as information technologies, combinatorial technologies as well as experiment design. Whatever the technology and wherever they are employed, it is critical that they be identified. Outsourcing will introduce significant contingencies and expose the organization to unnecessary external influence (cf/ Section 3.1.2). As a general rule, outsourcing or sharing must be avoided when the technology is *core*.

5.4. External Sources of Knowledge. Under conditions of turbulence and complexity, the organization's science and technology assets and strengths must be developed as fast as the science frontiers advance. One observer stated:

> . . .even a constant rate of technological change implies that from one period to the next, the absolute amount of change—and the corresponding technological and managerial challenge—increases exponentially. . .. [And] once a firm obtains a knowledge-based competitive edge, it becomes ever harder for competitors to catch up (27).

To sustain a constant accretion of knowledge in the context of rapidly advancing frontiers, however, R&D leaders must make use of knowledge sources external to the organization. This is not in contradiction to the warning against out-sourcing core technologies (above). Rather, it is an explicit acknowledgment that, under conditions of turbulence, developing internal capacity requires *bringing external knowledge sources in-house*. Knowledge must be captured continually. To achieve and then sustain competitive advantage, R&D leaders must include sources such as other organizations and new recruits.

Which firms to acquire or organizations to partner with, and which talent to recruit, are extremely important technology strategy decisions that should be based on a positive response to at least the following four questions. First, will the external knowledge source, in people's best judgment, support the organization's future domain? Domain encompasses products or services, populations to whom the products or services will be provided, and technologies by which they will be produced (29). Under conditions of turbulence, there will be events and issues that will affect each aspect of the latter. Social support and political will can make some products or services more or less attractive; other events can make products or services more or less important. The fit of external knowledge sources must be based upon their ability to support the expected future, not the present, domain.

Second, will the external knowledge source, in people's best judgment, provide a unique competitive advantage? Candidate knowledge sources should not be obvious to the competition. If the set of candidates that R&D leaders are considering is on every other company's scouting list, those sources will not provide a competitive edge. Leaders who have a sophisticated understanding of technology are more likely to cast their net very widely and early, so the candidate sources can provide unique advantage.

Third, will the intended investment in each external knowledge source, in people's best judgment, be sufficient to build the R&D resource meaningfully? Candidate knowledge sources will have been identified because it is presumed that they can add to the organization's R&D capability. However, the amount available to be invested in them must be sufficient to build that resource in a meaningful way. Too little invested is, like too late invested, a waste of money.

Fourth, in people's best judgment, is there evidence that the values actually held by the candidate knowledge source are consistent with organization's strategic vision? Although last, this is one of the more critical issues, because it is not solely knowledge from an external source that is captured. Selected organizations and individuals also bring their own values. For example, is there evidence that new recruits have experimented and failed? Is there evidence that they have learned from failure? Is there evidence that their career has been "eccentric" to the norm (eg, did they ever study or work in very different disciplines), and so on?

The questions relevant at an organizational level are similar. Based on actual performance data and the observations of outside experts, has their work really been on the leading edge or defining the leading edge? What is the evidence that the organization encouraged experimentation and supported failure? What is the evidence that learning occurred? Has the organization's evolution been eccentric to the norm?

A useful test of values is for in-house scientists to observe the behavior of potential recruits and people in organizations being considered for acquisition and then to consider the following questions: What interests them? What excites them? What kinds of questions do they ask about the scientists' own organization? Such observations provide insights into the values actually held. For example, taking (intelligent) chances reflects a risk willing attitude, the value of risk willingness, and an orientation towards science and technology of at least remaining on, if not defining, the leading edge. Lack of failure, of an individual or of an organization, should warn people that safety and mediocrity may be prized.

5.5. Organizations and People. All four criteria for judging the fit (or not) of external knowledge sources for the organization are concerned with finding and integrating people. This section ties together *organizations* and *people*.

The first criterion (support of the firm's *future domain*) can be restated as two questions: Do the people have knowledge, skills, and capabilities that are germane to the firm's future products and markets? Is there any evidence that they are able and willing to share their knowledge with the program and project teams in which they will be integrated?

The second criterion (*competitive uniqueness*) can be restated: Are the people familiar to many other firms or a few? The more active team members are in their respective invisible colleges, the more readily they will spot people who bring a unique competitive advantage, because they are relatively unfamiliar to competitors. Membership in the knowledge network is not only a potential barrier to entry, but also a vehicle for discovering unique external knowledge sources.

With regard to the third criterion (*knowledge sufficiency*), external knowledge sources have been identified because they are presumed to be capable of supplementing the firm's current capability. However, the sufficiency criterion is determined only partly by the source's scientific reputation, vitae, and stated accomplishments. More important are the judgments of team members about the demonstrable value-added they believe the people will provide. At the end of the day, knowledge sufficiency depends on new recruit's willingness to share their knowledge and experience with program and project team members.

In terms of the fourth criterion (*values*), external sources bring not only knowledge (person-embodied) but also values (person-embodied). As noted above, the litmus tests for value "fit" are the initial interactions between external people and team members. Internal scientists must observe people's behavior, to discern what interests and excites them. From these observations, they will make some inferences about what values people may actually hold. Team members must then decide if those values are consistent with their own desire to be consistent with the strategic vision and technology strategy.

5.6. R&D Programs and Projects. Within the reframed definition of technology strategy, R&D programs and projects can be viewed as *booster rockets*. They are both the sources of energy that propel the organization towards its strategic vision and the means by which R&D vector coordinates are adjusted. Fundamentally, strategy is embedded in projects:

> There are two ways in which strategy is embedded in projects. The pre-project phase encompasses the activities by which the firm establishes its priorities and identifies the technologies it expects to be involved in future projects. The post-project phase governs the ability of the organization to learn from one project to the next, to assess the effectiveness of organizational or technical approaches employed, and to make improvements that, over a series of projects, will leverage project experience into a more innovative system (27).

The technology trajectory can be sent off course by poor decisions that result in programs and projects that are in inappropriate areas, or are underfunded, or are badly managed so they fail to achieve their objectives. Any program or project that is poorly executed affects the R&D vector, which affects the technology trajectory and, ultimately, organizational viability. R&D programs and projects always face the prospect of scientific and technical wrong turns and apparent dead-ends. That is the nature of science. Failure is unavoidable and an opportunity for learning. Effective R&D leaders take this into account, so that failure is not catastrophic for the organization. However, poor decisions at the program and project level can propel the organization as far from the strategic vision as if it were struck by a meteorite.

Good strategic decisions, those that result in strategic success, depend upon good communication, no matter how large or how small the organization. Because of the tight linking of program, project, R&D, and institutional decisions, team members must continually seek out and interpret data and communicate relevant information wherever needed to other members, team leaders, R&D directors, people in other divisions and functions, and/or senior management. Similarly, information that affects the teams must be communicated in timely fashion from wherever it originates. Because of the tight linking, decisions at all levels must be informed decisions.

At a minimum, good communication means that:

- People are well-informed by means of sophisticated information technologies and data sources that are accessible on a "want to know" basis (31).
- They are candid in their discussions.
- They freely challenge and surface assumptions.
- They exercise good judgment.
- They discuss the business of the organization, without regard for function, title, status, etc., and without fear of reprisal.

Program and project team members are especially reliant on, and responsible for, good communication and effective decisions. They need timely information to respond appropriately to what is happening in the macro-environment, and they are likely to be first to find out about rival organizations' scientific success or failure, emerging problems, and other data crucial to the organization. R&D teams provide critical input to the question: "What is the impact of an event or issue that has been identified?"

Team members' involvement in gathering intelligence and monitoring weak signals can make the difference between intelligence and strategic intelligence. They must operate at the highest level of strategic sophistication. Moreover, their function is not simply to gather strategic intelligence, but to appreciate how the information may be used instrumentally. If team members are not strategically sophisticated, it does not matter if R&D and institutional leaders are strategically sophisticated.

It is also important that team members be actively involved in the respective "invisible colleges" that, taken together, constitute the organization's membership in the knowledge network. Such membership can be a critical barrier to the entry of competing firms, and it can provide useful information regarding external knowledge sources.

Finally, core technologies are by definition those in which there is a sizable amount of tacit knowledge, knowledge that resides in people's minds, as opposed to codified knowledge in a report or article. Every team member should be viewed as a repository of potentially powerful competitive advantage to the organization. If a team member from a core technology leaves, the tacit knowledge content of that technology is reduced and the organization's competitive advantage weakened to a greater or lesser degree.

6. Conclusions

Modern R&D is very different from the activities that characterized R&D for more than a century, up until the latter decades of the 1960s. These differences must change the way strategy is perceived and then designed, how work is organized, and what information technologies are utilized, among other things. However, these differences must not distract leaders' attention from the primacy of individuals and the institution in which they work. To reiterate, it is *people* who generate the ideas in an *organization* that helps or hinders the process of innovation. The effectiveness of the latter process, in turn, determines the success or failure of projects and the output that benefits nations.

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Table 1. **Competitive Technology Strategy**[a]

	Spheres of technology action	
Spheres of management action	*Use*	*Advance*
corporate	with R&D, defines unique technology identity; sets R&D budget	with R&D, changes identity and budget as appropriate (where? when? how? based on?)
research	selects discovery programs, research projects; allocates resources; assesses new information and data; communicates information	changes priorities and allocation (where? when? how? based on?)
development	selects projects; allocates resources; assesses new information and data; communicates information	changes priorities and allocation (where? when? how? based on?)
program and project	determines concept viability; carries out efforts; seeks and interprets new data; communicates information	changes decision criteria (where? how? when? based on?)

[a]Ref. 26.