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Commercial Industry Research & Development Management Best Practices

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Executive Summary

This paper reports the results of research by the Institute for Defense Analyses (IDA) conducted for the Office of Cost Assessment and Program Evaluation (CAPE), Office of the Secretary of Defense (OSD) on current commercial industry practices for organizing and managing research and development (R&D). The focal question was, "How does industry place its R&D bets and manage R&D outcomes to meet corporate goals?" IDA performed a literature review to define terms, identify trends and issues, and develop questions for interviews with industry R&D leaders. IDA interviewed R&D leaders at seven large U.S.-based companies with significant R&D programs to better understand real decisions about R&D organization and management. Interviews were provided by executives from the following companies: Applied Materials (AMAT), The Boeing Company, Exxon Mobil Corporation, General Electric (GE), IBM, Intel, and Proctor & Gamble (P&G).

R&D Strategy and Overall Management

Based on changing competitive market environments many large U.S. companies have fundamentally refocused, reorganized, and rethought their business practices, including the R&D they conduct to keep pace with rapid technological change and to improve their business results.

Four themes are common among leading research-oriented companies:

1. R&D is managed for business results, even for exploratory projects.
2. Companies are increasingly accessing R&D from outside the company and integrating it with internal R&D, rather than depending primarily on internal discoveries.
3. Technology thrusts are explicitly derived from the company's strategic perspective on how its R&D should be aligned with business goals.
4. Setting and maintaining technology development direction is a top-level corporate responsibility.

A key focus of the study was how industry leaders measure and assess the results and value of R&D, and how they manage the R&D process by using this information. This includes:

- Developing a clear, coherent strategic direction and plan
- Managing to get results out of the R&D process
- Broadening the sources of new ideas and integrating these into the firm
- Measuring and assessing the results and value of R&D

An important step taken by most firms reviewed is a structured process for corporate and business unit management to design a clear, coherent plan or roadmap for implementing the innovation strategy. This plan elaborates on which units are in charge of what activities and when they should be completed, and connects individual project roadmaps to overall organizational vision. It also establishes requirements for a business's long-term success—in other words, evaluation metrics beyond the next quarter's earnings.

To effect a more strategic, results-oriented R&D management system, many companies have restructured their R&D. One major shift has been the reduced role of central R&D laboratories. Companies have also sought R&D from outside the company through venture investment and endeavored to make R&D more productive by creating internal corporate entrepreneurship groups and through various open innovation approaches. Open innovation entails R&D and new product development partnerships with end-users, suppliers, competing firms, and research institutions—all of which are increasingly commonplace. Many technology-focused firms have determined that partnering with others who have different knowledge and capabilities achieves much better results in developing and implementing new concepts and products. Open innovation is a relationship not just an acquisition.

In linking R&D outcome to long-term financial performance, most of the firms the IDA study team interviewed made it clear that the chief executive officer (CEO) and the chief technology officer (CTO) fight hard to maintain R&D funding as a strategic investment that should not be perturbed by business fluctuations—especially overall revenue.

R&D Portfolio Planning and Assessment

Leading firms that invest substantially in R&D have well-defined and assiduously monitored assessment processes. Most of these companies explicitly start with the definition of the value of R&D in their corporate strategy, which is usually expressed in terms of how and in what way R&D contributes to the firm's ability to effectively and competitively introduce and produce new products. R&D is about *results* and therefore it should be measured more in terms *of impacts*, not inputs and the internal R&D activities themselves.

Leading technology companies focus a great deal on developing a portfolio mix and managing the portfolio relative to explicitly defined (deliberated and negotiated) strategic goals. Portfolio development and assessment is a strategic enterprise usually under the CTO but with high-level business unit involvement. Portfolios may be defined in many ways, including 1) distribution of projects across businesses; 2) allocation to single businesses versus enabling or cross cutting platform technologies; 3) internal versus external capabilities; and 4) allocation for potentially new businesses versus current businesses.

Project portfolio management refers to the management of a group of related projects within the company, focusing on maximizing the value of the portfolio through management of resources. In another related approach, *innovation portfolio* management, executives develop a strategy to select and develop new concepts, connecting them eventually to *project portfolios*.

R&D Project Management

A key takeaway from both the literature and interviews is that R&D needs to be organized and managed in different ways for different stages. Thus, the relevant managerial question for early-stage opportunity creation is how to generate more and better targets. Which people, which structures, which strategies can be employed toward more effective idea generation for these objectives? Later, as a technology is ready to be transitioned and scaled into commercialization, the focus is on deployment success with tight control.

Stage-gate Process

The R&D management literature and IDA's interviews show that most technology-based firms use some form of stage-gate process (that is, a structured framework for assessing projects) in their R&D management. From this review, some specific lessons and perspectives come to the fore:

- The key question is making the stage-gate process stick. That is, how to use it to actually stop projects and programs that are not performing.
- How to employ the stage-gate process and who to involve in it depends largely on technology horizon and strategic importance of the technology—it is not a "one-size fits all" approach.
- Detailed analyses must underlie the stage-gate assessment: Are milestones and performance metrics being met? Are there identifiable impediments to success? Has the product / market environment changed?

Leading firms use rigorous, but specifically designed stage-gate processes to manage the *cost* of failure. The objective is not to prevent failure per se, because that implies lack of innovation and exploration of new ideas. Rather the focus should be on *encouraging risk-taking in exploring new ideas early-on,* while employing disciplined processes, such that:

- The rejection rate of projects are highest in the early stages of ideation when the costs of the project are lower.
- The stages represent milestones at which a new level of investment is needed to move forward.
- The objective is to manage the business risk while testing key assumptions.

Many firms have embraced the Technology Readiness Level (TRL) concept. TRLs assessments are explicitly used in the technology gate decisions. As one example, GE uses a rigorous "tollgate" project assessment process. "At GE Research success is not just getting a project done – it's making the right decision… If a technology development will not achieve the required [specified] results, then "success" is killing it sooner rather than later."[1] Thus it is recognized that success is not just getting through the tollgate, it is determining whether a potential technology should get through based upon accepted tests and criteria.

Transition and Scaling

Any new product offering has a set of risks beyond the technical performance and capabilities of the product, including the unknowns of the future market, the availability of financing for scaling into production, and the firm's own internal capabilities to absorb and effectively manage the new product's entry into production and marketing. Therefore determining how much risk to take on in introducing a new product (and attendant production processes) is a crucial decision that the firm must make—essentially it is an informed bet based on judgment, experience, as well as customer-focused competitive assessments. From the review of the literature and the interviews conducted, *the most prominent lesson* IDA learned regarding transitioning technology is that *frontrunner companies assiduously avoid introducing immature products and processes.*

Conclusions: Implications for Department of Defense (DOD)

The organizational context of Defense R&D, in contrast to private industry, must be carefully differentiated: DOD conducts R&D within its own governmental institutions, such as the defense labs, but also funds R&D through contracts to a wide range of performers—defense contractors, universities, private firms. In this regard, DOD is the developer and acquirer of systems for its own use that it pays others as contractors to provide. Thus, DOD is the *customer* who specifies its needs and formulates these into requirements that become embedded into the R&D and acquisition systems for others to execute. Commercial industry inherently has much clearer and specific metrics of results than does DOD. Generally commercial firms define results in terms of financial results, particularly profits and revenue growth. Many firms recognize that in technology-driven businesses R&D can provide important means to identify, develop, and implement new products and related production processes that provide the basis for growth. Measuring the value of DOD R&D is much more difficult because the desired goal is the much broader notion of sustaining and maintaining national security.

Practices for Consideration

These differentiating factors make the direct implementation of commercial industry R&D management best practices in the DOD challenging, and in some cases, inappropriate. That said, the following commercial industry best practices for R&D management merit assessment in the DOD context:

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[1] IDA interview with GE Global Research executive, August 26, 2011.

- Top corporate leadership is actively involved in setting direction for R&D and then making course corrections. The active involvement of very senior management is deemed necessary by most of these firms as essential to commercializing technologies.
- Corporate, business unit, and innovation strategies are explicitly linked.
- Best practices include a coordinated and coherent corporate effort to execute open innovation. This involves scouting for technologies outside the company and industry collaborations.
- Stage-gate processes are successfully employed based on their being applied early in the flow from idea to product. It was generally applied at the equivalent of transitions between DOD's Applied Research to Advanced Technology Development (Budget Authority 2 (BA 2) to BA 3) while the DOD 5000 process picks up at Milestones Materiel Document Design (MDD), A, and B.
- Stage-gate processes generally have serious early involvement of marketing and manufacturing organizations, and are empowered to modify or terminate R&D efforts. An important objective is to stop low potential projects early.
- Generally these companies assign a champion, often self-selected, to a promising project. This person provides strong business guidance to the project team.
- Identifying potential customer needs involves serious research to ascertain market potential.
- Commercial portfolio management is employed across the spectrum from research through development.
- Transition planning is an important issue addressed early in development by commercial companies. Leading firms do not attempt to transition immature technology to manufacturing.
- Among the companies studied, there is generally long-term commitment of people to projects.

Observations

Cost, schedule, and performance are the essential tradeoffs in determining a development strategy for a product. Achieving demanding technical performance objectives within cost and schedule constraints often is a key challenge for high technology development organizations. Many commercial firms employ a well-articulated and tightly managed spiral development process to address these competing criteria in a satisfactory manner over time. The question is whether this type of process is applicable to defense systems, which are of a much different scale, often stay in the field for decades, and for which interoperability is a key factor. If such spiral development processes were to be employed in DOD, IDA's view is that R&D

management approaches would be needed similar to those of commercial industry for assessing technical performance early in the process.

The concept of portfolio management is deeply embedded in the R&D management of commercial firms. The portfolio is a strategic-set of projects, such as the innovation portfolio. Could such portfolio thinking be applied better to DOD programs? As stated in a recent IDA study, effective analytic approaches to defining, assessing, and managing such portfolios has not been implemented within DOD.[2]

A leading industry R&D trend is open innovation. DOD could learn and adopt commercial best practices for finding and tracking commercial and government investments. The trend in commercial industry is to partner with others in developing new capabilities. Industry executives emphasized that DOD's role in partnerships with their firms has been a crucial factor in their ability to take on risky projects.

While commercial management approaches to R&D management will be difficult to employ across the board in DOD, the alternative is the current approach, which has led to results that many consider unsatisfactory—programs that take too long, cost too much, and often fail to deliver needed capabilities.[3] Therefore, DOD should consider:

- Efforts to attract more outside collaborations with R&D partners
- Developing and employing tools for evaluating technology development through partnering with external R&D performers linked to its own labs
- Ways to improve how it finds, evaluates, and engages new R&D partners
- Undertaking a benchmarking study on best practices for collaborating with university R&D performers as well as others
- Assessing how stage-gate assessment could be employed early-on and throughout DOD R&D so that programs that do not demonstrate appropriate value are restructured or terminated
- How private industry processes for measuring returns on R&D investment might provide guidance for ways to measure the results of defense R&D investment
- How to implement and assess a portfolio approach based on strategic objectives across DOD over distinct time horizons
- Developing platform technologies and approaches to transition platform technologies across multiple weapons systems, especially across multiple defense labs, acquisition program offices, and Military Services

[2] Porter, Gordon and Kneece, 2011.

[3] Porter et al., 2009.

- Developing its own incubator programs (including technical assistance and early stage commercialization-transition funds) to help it better engage small and medium sized enterprises (SMEs) and non-traditional suppliers (both large and small)

Contents

Appendices

1. Study Approach and Method

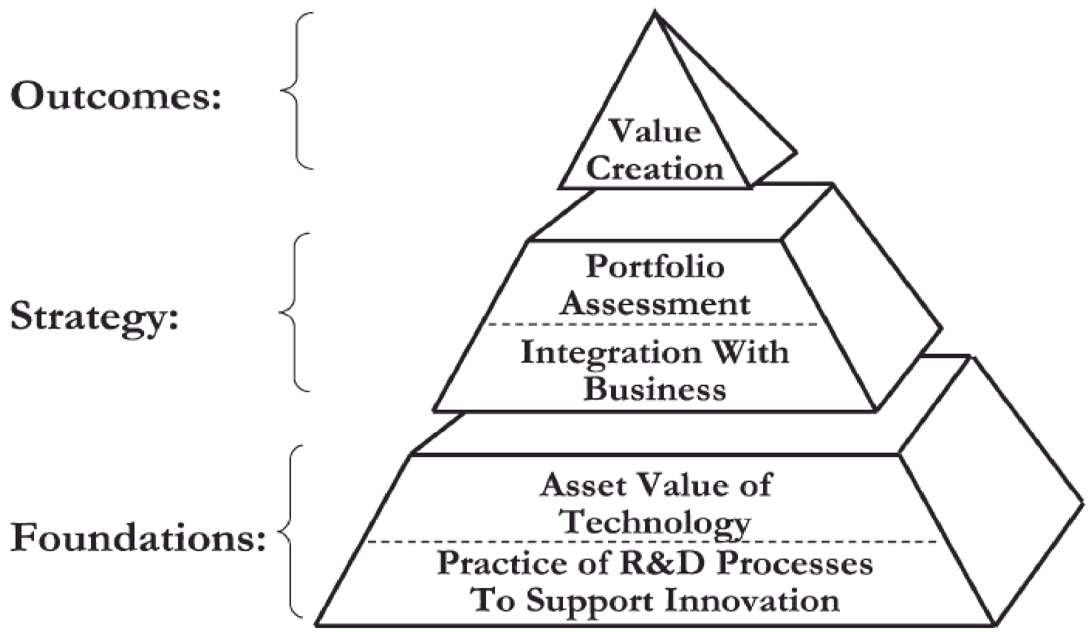
This paper reports the results of research by the Institute for Defense Analyses (IDA) study for the Office of Cost Assessment and Program Evaluation (CAPE), Office of the Secretary of Defense (OSD) and focuses on current commercial industry practices for organizing and managing research and development (R&D). The focal question was, "How does industry place its R&D bets and manage R&D outcomes to meet corporate goals?"

The IDA study team performed a literature review in order to define terms, identify trends and issues, and develop questions for interviews with industry R&D leaders. IDA reviewed eighteen books and dozens of articles in eighteen journals, focusing on recent publications (2005 to 2011) and those that cite specific companies and practices. The IDA study team then interviewed R&D leaders at seven large U.S.-based companies with significant R&D programs in order to better understand real decisions about R&D organization and management and to elicit current perspectives and insights. The companies providing interviews were Applied Materials (AMAT), The Boeing Company, Exxon Mobil Corporation, General Electric (GE), IBM, Intel, and Proctor & Gamble (P&G). These companies were selected based on the literature review, reputation, and sponsor interest.

The following chapters document and synthesize the findings from the literature review and interviews:

- R&D Strategy and Overall Management
- R&D Portfolio Planning and Assessment
- R&D Project Management
- Transition and Scaling

Figure 1 depicts relationships among these categories. The ultimate goal is value; in the case of industrial enterprises, the business results of interest are usually financial and market based, including profit and revenue growth. However, underlying these goals are the management and assessment of the means for achieving profit and growth, such as the introduction of new products, exploration, development and implementation of new production processes; or identification and sourcing of external capabilities that augment or sustain existing business areas or provide the basis for new ones. For firms in technology-based industries, R&D is key to developing these new product and production capabilities. How R&D contributes to these goals and how it can be managed to these ends is seen to be critically important to such firms. These firms explicitly plan, manage, and assess their R&D processes and its output based on a carefully articulated strategy. Strategy is about setting a direction, specifying value-based criteria for portfolio management, and business integration. Business integration is largely about moving successful product and process development projects into operating businesses and scaling them for results. Effectively managing the projects themselves focuses on making decisions on their prospects for success based on well-defined metrics and processes for evaluating risks and focusing on those projects that can provide greatest value while, as early as possible, terminating those that will not. Crucial to attaining value is the ability of the firm to move those selected incipient product and processes into fruition by transitioning them into an existing production environment or establishing a new business enterprise for this purpose.

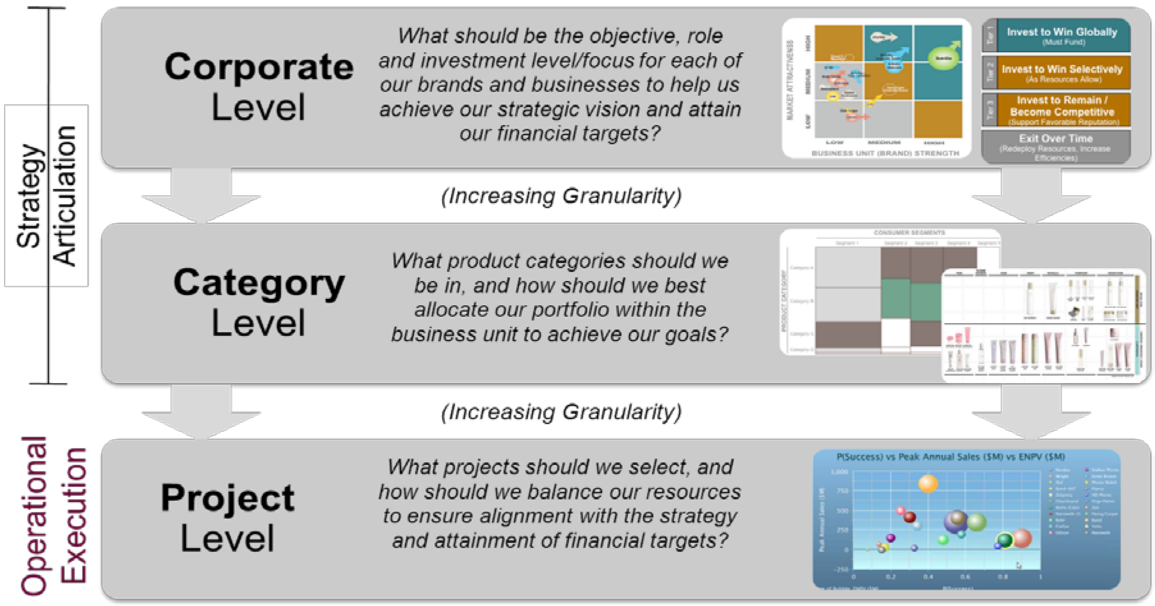


Source: *Research-Technology Management*, Sept–Oct 2001

Figure 1. R&D Strategy and Management is About Achieving Results from Innovation

This paper sequentially reviews current industry approaches for R&D management starting with a chapter on R&D Strategy and concluding with Transition and Scaling. Each of the chapters includes best practices to support innovation and are followed by synopses of R&D management practices at the seven firms that provided interviews. The study concludes with some observations on how these R&D management practices might be relevant to the Department of Defense (DOD).

Figure 2 depicts how R&D portfolio management can be applied at different levels.



Source: Clareo Partners, LLC

Figure 2. Setting R&D Priorities Occurs at Multiple, Related Levels

2. Research & Development (R&D) Strategy and Overall Management

Industrial R&D has changed substantially in the past twenty years. R&D is still perceived as key to sustained market leadership in products and related production processes. But in highly competitive global markets, companies are increasingly facing a "Red Queen" effect, to borrow a metaphor from Lewis Carroll's *Through the Looking-Glass*:[1]

> "Well, in our country," said Alice, still panting a little, "you'd generally get to somewhere else—if you run very fast for a long time, as we've been doing."
>
> "A slow sort of country!" said the Queen. "Now, here, you see, it takes all the running you can do, to keep in the same place. If you want to get somewhere else, you must run at least twice as fast as that!"

Based on changing competitive market environments, many large U.S. companies have fundamentally refocused, reorganized, and rethought their business practices, including the R&D they conduct in order to keep pace with rapid technological change and to improve their business results. Large firms' core businesses are under siege from small ventures and new foreign entrants while technology and product innovation combine to offer prospects of new markets that could be the drivers of revenue growth, but also may presage the obsolescence of existing businesses. This chapter will cover the following aspects of overall R&D strategy and management:

- Setting Strategic Directions
- Management Approaches
- R&D Organizations and Operations
- Open Innovation

A. Setting Strategic Directions

For leading companies, formulating and enforcing a clear, coherent strategic direction and plan for R&D is the foundation. What are the trends and forces shaping the industry, and how will the company position itself with respect to changing market conditions and competition? Does the company need to seek new businesses based on technical breakthroughs (*radical innovation*) or is it sufficient for R&D to support existing business units in upgrading, modifying

[1] The Red Queen race is used as a metaphor for innovation management in Baumol, 2010.

or extending current products and services (*incremental innovation*)? Is R&D being pursued as a hedge against potential future scenarios in which the core business would be threatened?

Proctor & Gamble's then-CEO A. G. Lafley expressed the pressures for redefining and restructuring R&D to meet new strategic realities: "Our challenge was three-fold. First was, we defined innovation way too narrowly. We defined it around the technologies, the chemistry, and we were sort of running a "push" innovation system. Secondly, we weren't executing very well. We were running industry-average success rates and, in our industry, 80 to 85 percent of new brands and new products fail, so we were only succeeding 15 to 20 percent of the time. Thirdly, we really weren't facing up to the realities of what had become a much more competitive, global, unpredictable, disruptive marketplace."[2]

R&D strategy also varies based on the fundamental demands of particular industries. In industries involved in complex system integration, such as aerospace, automotive, machinery, and information networks, keys to success are managing interfaces and supplier networks, and capital costs can limit the ability to test multiple variations. Companies that focus on inventing technologically advanced components require expertise at the boundary of science and manufacturing in markets that are often turbulent. Science-based industries such as chemical, pharmaceutical, and agriculture face regulatory hurdles that determine which products can come to market. Consumer products companies emphasize cost and efficiency, and flexibility is a competitive advantage in adjusting to quickly-changing market demands.

The role of R&D will be different in each of these cases, as will the people, resources, organizations, and tools necessary to accomplish the company's mission. However, four themes are common among leading research-oriented companies:

1. R&D is managed for business results, even for exploratory projects.
2. Companies are increasingly accessing R&D from outside the company and integrating it with internal R&D, rather than depending primarily on internal discoveries.
3. Technology thrusts are explicitly derived from the company's strategic perspective on how its R&D is aligned with business goals
4. Setting and maintaining technology development direction is a top-level corporate responsibility

Some examples from the interviews illustrate these themes: Applied Materials has adopted a partnership-driven strategy coordinated around explicit roadmaps, while it leverages its technical strengths to create major new product thrusts. Intel bases its R&D tempo on the well-defined product/process roadmaps in the integrated circuit industry. Exxon-Mobil maintains a technology implementation organization to bring new capabilities to the field for high risk exploration programs. IBM has moved away from a traditional lab science and technology

[2] Anthony, 2008. (Interview with P&G's then-CEO A.G. Lafley.)

(S&T) focus to one more integrated with corporate business development, though they have maintained a significant science program. P&G has transformed its central laboratory to focus more on external partnerships, going from Research and Development to “Connect+Develop.”[3] In order to keep abreast of (and selectively access) leading edge scientific discoveries and emerging technologies that could disrupt the current business, many companies are building relationships with universities, research laboratories, and venture capitalists.

Once a corporate strategic vision of competitive aspirations and growth goals is set, companies need to translate these into specific R&D objectives that are tied to measurable value-creation milestones. R&D is increasingly integrated with corporate acquisition activities and venture funds to support broader corporate entrepreneurship efforts aimed at new business models in addition to product-focused work.[4] IBM, for instance, has created a special process for “Emerging Business Opportunities” that leverages its technology base to develop businesses in adjacent markets. General Electric has implemented a process called “Session T” for identifying and prioritizing such opportunities through structured brainstorming on customer needs and the market, linked to technology options from Global Research that may be applicable to the needs. The Session T process helps GE determine what R&D is worth pursuing and how it is aligned with business needs. Much of Apple’s success has been attributed to its ability to redefine and shape markets with combinations of products and services that go beyond what current customers have experienced or even know about. To emphasize the business-building focus of its technology efforts, Apple does not refer to its engineering design work as R&D.[5]

In leading companies, the organizational elements of R&D execution, such as resource allocation and designation of areas of technical interest, are determined through a top-level technology strategy process. An accountable executive, usually the Chief Technology Officer (CTO), works with business unit (BU) and R&D leaders in formulating the strategy. Boeing, for instance, redefined its advanced research organization.

Still, a fundamental problem in R&D management is that long-term investment in R&D is vulnerable to near-term demands. A key role of the CTO (and sometimes the CEO) is to explain, defend, and protect long-term and exploratory investments. The CTO may also provide general

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[3] Brown and Anthony, 2011.

[4] Wolcott and Lippitz, 2010.

[5] Apple is known for de-emphasizing the notion of R&D and instead places its focus on insightful product design. There is some definitional ambiguity in this as it is likely that a considerable amount of what Apple deems to be product design other firms would include as the development aspect of their R&D. Apple is relatively quiet about its R&D, and downplays it relative to product design. An interview of former Apple CEO John Sculley by Leander Kahney (2010), “John Sculley on Steve Jobs,” provides a number of insights on Apple’s approach to product development. There have been an array of blog discussions on Apple’s R&D relative to other high-technology firms, but not much published in the management or business literature on the topic directly. See “Apple's Research and Development Humbles Other Tech Companies,” http://seekingalpha.com/article/197583-apple-s-research-and-development-humbles-other-tech-companies.

program oversight, particularly early-stage opportunity identification and prioritization.[6] In companies where R&D is performed primarily within BUs, the CTO may review and approve R&D funding cuts. For example, GE's photovoltaics business is yet not delivering significant earnings today but is viewed as an important long-term opportunity. Therefore, the program is overseen directly by the CTO until it matures, rather than being managed by the company's Building and Construction BU. At the same time, the CTO may also have a role in shelving low-priority projects and redirecting resources.

An important related topic is R&D spending during general economic downturns. Most of the firms interviewed made it clear that *the CEO and the CTO fight hard to maintain R&D funding as a strategic investment* that should not be perturbed by business fluctuations, especially overall revenue. Intel's former-CEO Craig Barrett, quotes Gordon Moore, "You can't save your way out of a recession. You can only invest your way out of a recession."[7] He elaborates:

> …it's new products and new technology that create the demand for your products. Unless you have new technology and new products, there's no new demand. So the only thing you can do in a recession is, in fact, to continue to invest and create exciting new products.

CTO Dr. Omkaram Nalamasu of Applied Materials stated that internal R&D at the company has remained around one billion dollars per year over the past several years, while revenues have fluctuated given the perturbations of the semiconductor market. He stated specifically, "Applied tends to spend more in R&D in downtimes."[8]

Clearly R&D expenditure cannot be totally divorced from revenue. First, most of the firms the IDA study team reviewed link corporate performance and R&D, and thus they see revenue growth as being a function *of properly executed* R&D. The reverse side is that declining revenues or the corporate competitive position have caused major changes in many companies' approach to R&D.

For instance, IBM Research has evolved from a traditional independent Research Lab up to the 1970s to a greater focus on a clear link from R to D to manufacturing. The economic recession in 1982 forced IBM to focus on "tightening the ship" with a greater emphasis on connecting R&D to business results. In the 1990s, new CEO Gertsner determined that R&D was a substantial strategic asset for IBM, but also insisted that the company needed to get much more responsive results from its R&D. He therefore directed a fundamental redefinition of the Research Division as will be discussed below. Even with such changes in direction, IBM R&D

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6 Banholzer, 2010, 24.

7 Barrett, 2010, 40–43.

8 IDA interview with Dr. Omkaram Nalamasu, CTO, Applied Materials, July 7, 2011.

has remained about 6 percent of revenue even through downturns. R&D in 2001 was $5.3 billion and in 2010 it was $6 billion, while revenue grew from $86 billion to $100 billion.[9]

B. Management Approaches for Implementing the R&D Strategy

It is the job of corporate management to spearhead the development of an effective R&D/innovation strategy, oversee the management of innovation activities, and selectively participate in the guidance of these activities as necessary. Innovation links R&D processes and outcomes to the broader new business creation activities of the organization, both short-term and long-term. It encompasses improvements to existing products, generation of new products, and foundational technical expertise to support creation of new businesses. Innovation is increasingly consumer-driven or end-user-driven but not just based on projections from current or near term customer demand. Rather, highly innovative firms employ several approaches to *anticipate* the interests and needs of the consumer or end-user.

Many (but not all) organizations establish high-level boards whose primary function is to be stewards of the company's research activities and to evaluate emerging areas of interest. These boards assume several responsibilities, including connecting and overseeing networks in disparate business units, creating, managing, or supporting business ventures in new fields, and connecting customer researchers, engineers, suppliers, and outside parties during the design and production process. They assume names such as an "innovation board" or an "Emerging Business Opportunity program," and frequently consist of managers of leading groups as well as a senior executive such as the CTO or CIO. An example of such a group is Boeing's Enterprise Technology Strategy organization, which reports to the CTO and is responsible for developing "a companywide strategy for determining critical technologies and has invested hundreds of millions of dollars into key research and development areas to maximize yield and technology readiness throughout the company."[10]

Some firms assign a set of emerging business projects or a "strategic thrust area" to each manager, who reports progress back to overall corporate management. In general, their stewardship is not judged based on revenues but rather using technological or product development benchmarks—such as number of new products brought to market within a specified time. Funding generally comes through pathways directly from corporate leadership, but at times, as at GE, these are essentially imposed as taxes on the current business units but allocated through a broader corporate process.

An example of this strategic management approach is the development of Raytheon's homeland security business in the early 2000s, which resulted in rapid growth in a new business area. Then-CEO Dan Burnham tasked the vice president and general manager of Raytheon's Strategic Systems division to lead a new homeland security venture. "…the 'DNA' for startup

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9 Van Atta et al., 2003.

10 IDA interview with Boeing executive, July 27, 2011.

had four principal components: 1) the organizational relationship to other operating divisions; 2) seed funding for startup; 3) the course of funds for continued growth; and 4) the rules of engagement for facilitating cooperation and collaboration with executives running other mainstream operating divisions."[11] The new business was only given $5 million annually in order to ensure that they worked with the utmost agility and focus and maximized the use of existing technological resources for new purposes (a process called "exaptation"). However, funding support from other units would be rewarded with a proportionate return of revenues *back to the unit*, a policy that immediately spurred participation from across the company. As for the management structure, the homeland security business was not formally established as a separate business unit in order to minimize inter-unit competition and administrative overhead, which could easily overwhelm such a fledgling venture. To simultaneously maximize high-level support, Burnham opted for the business to report directly to him. In 2008, Raytheon's homeland security business group generated $2 billion in revenue.

An important step taken by most firms reviewed is a structured process for corporate and business unit management to design a clear, coherent implementation plan or roadmap for implementing the innovation strategy. This plan elaborates on which units are in charge of what activities and when they should be completed, and connects individual project roadmaps to overall organizational vision. It also establishes requirements for a business's long-term success—in other words, evaluation metrics beyond the next quarter's earnings. The best companies assess the range of future markets, then map out what approaches can get them to good competitive positions in those futures, and only then make technology roadmaps to help them point their research in the right ways.

Every spring at GE, the Strategic Plans and Growth Playbook is developed to determine technology needs for multi-generational technology plans. In the fall, the focus turns to developing the technology roadmaps to meet these needs. Once the product roadmap and technology needs are identified, GE establishes direction on addressing technology needs and sets a strategy. GE has established a specific process for addressing this—"Session T"—that brings together the commercial team's executive leadership, the product manufacturing and technology development teams from the business units, with Global Research researchers from technology areas, and selected customers. This process addresses what R&D is worth pursuing and how it is aligned with business needs. The output is then presented to the Executive Council for review, which then sets high-level challenges for business performance metrics. With the identification of the technologies needed, the next question is how are they going to be accomplished? Will it be done primarily by the BU research unit; inside GE Research; with external partners? These results then feed the fall planning process that sets the company's technology strategy.

[11] Meyer and Poza, 2009.

Similarly at Dow Chemical Company, a playbook is created that includes project descriptions, ranks, resource data, milestones, risk-adjusted returns, and other data about each business's major R&D projects. Following the assessment provided by the playbook, the board itself must be ready to financially and organizationally support key projects and R&D activities even if they are not immediately profitable to their businesses, or if the firm is facing budget fluctuations. As described by a senior executive of Dow Chemical Company:

> …businesses are, by their very nature, preoccupied with quarterly results. The system is biased toward the short term, and in times of crisis, there is the potential for the long term to suffer. At Dow, before R&D funding is cut, there is at least one review at the corporate level to ensure the long term is sustained and balanced against the inherent short-term bias of the business.[12]

The Building Integrated Photovoltaics (BIPV) program at Dow is an example of its strategic corporate management. While such a program would usually be run by Dow's Building and Construction business, the programs large R&D budget and initially negative cash flow would have negatively affected the business unit and hampered Dow's long-term photovoltaics development because of fluctuations in resource availability. Therefore, the CTO directly oversees BIPV in consultation with senior executives, and it will only be turned over to the Building and Construction business once it matures and generates a positive cash flow.[13]

Another key function of corporate management is to inculcate and incentivize risk-taking and an overall culture of innovation throughout the organization. As one observer suggests, "Provide specific incentives for intelligent risk-taking by managers, and/or set specific penalties for failure to develop their quota of new products during an appropriate period of time. Many public corporations, in their annual reports, like to demonstrate their aggressive growth performance by pointing to the high proportion of their total revenue that is accounted for by new products introduced within the past two or three years."[14] At the same time, researchers and their managers need to specifically evaluate the scientific and technological feasibility of projects when considering new ideas. One example is Dow's assessment of the development of ethanol as a response to the increase in demand for renewable energy products. It was assessed technically that "the conversion efficiency of plants is only a small fraction (typically 0.1 to 1 percent) of the input solar flux, and that includes the energy captured in the roots, leaves, etc." As a result of this inefficiency, ethanol companies survived through government subsidies for a period of time, but, "when the price of oil collapsed, so did the price of ethanol. The result: bankruptcies. VeraSun, Aventine, E3Biofuels, and Cascade Grain Products are only a few of the well-known casualties."[15]

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[12] Banholzer, 2010.

[13] Ibid.

[14] Buggie, 2007.

[15] Banholzer, 2010.

C. R&D Organizations and Operations

As noted above, to effect a more strategic, results-oriented R&D management system, many companies have restructured their R&D. One major shift is the role of central R&D laboratories. Companies have also sought R&D from outside the company through venture investment and endeavored to make R&D more productive by creating internal corporate entrepreneurship groups and through various open innovation approaches as is discussed below. Thirty years ago, many large companies depended on their corporate labs to keep them in the technology innovation race. However, increasingly over the past two decades, company after company has refocused on product development. Some (like IBM and GE) still have substantial central laboratories, but even these are considerably different than they once were. The strong tendency is toward open sourcing innovation looking outside of the company for research in small companies and universities, both often funded by the federal government, and occasionally government laboratories, as well as various means of partnering with other firms. In short, big companies are shifting risk and cost to others by letting them perform the early riskiest stages of technology innovation. In return, these firms offer a means to bring these early ideas to fruition.

1. Central Laboratories

While most of the firms the IDA study team interviewed maintain central research operations, there are very different expectations from them today and they are managed accordingly. Specifically, the work of these laboratories has been much more clearly linked to product and business development. While there are some concerns that such closeness inhibits exploratory or longer-term research, it is clear that corporate R&D today has to demonstrate its contribution to creating and implementing new products. In fact, simply stated, the main purpose of corporate R&D today is to create new products—either for the existing business units or for new businesses.[16]

While product development is the main focus of R&D, many firms, some companies—especially IBM, but also Intel, GE, and others—do allow and even foster broader, more fundamental, and non-product-specific research. IBM makes this point explicitly: “We still do science and reward it.”[17] Intel Labs, under CTO Justin Rattner, look beyond integrated circuits (ICs) to consider possible future uses of and needs for computing from the end-users’ perspective, not the direct customer who buys Intel’s chips. Examples include oil and gas companies who use increasingly sophisticated modeling tools to search for deposits, notions of *context aware computing*, and the interface between the human brain and computers. Exxon-Mobil, whose research organization is very closely linked to furthering business results, notes

[16] It should be recognized that the R&D organization serves other functions as well, including providing expertise for overcoming technical difficulties with current production operations and providing technical capabilities to evaluate other firms that are prospects for acquisition. These other functions are generally ancillary to and supportive of the new product development role.

[17] IDA interview with IBM executive, July 28, 2011.

that R&D management must balance between following the research plan and giving the researchers "room to play." That is, even while using structured management processes, several firms IDA interviewed emphasized that management needs to be constantly aware that R&D is a creative enterprise and that over-management and bureaucracy can stifle creativity.

2. Corporate Venturing

Some companies have employed corporate venturing since the 1970s and 1980s, but in recent years it has become more sophisticated and connected to overall R&D and open innovation strategies. Corporate venture capital (CVC) organizations aim to supplement internal technical competencies as well as create a window into possible future directions. As such, it is important for CVC to be connected to internal technical talent, for due diligence initially, and then later to facilitate the absorption of lessons back into the company.

Methods of establishing a CVC vary. A company can invest as a limited partner in an established VC fund, as Coca Cola did with the Draper Fisher Jurvetson Element fund on water. It can set up its own VC fund with others as limited partners, as Unilever has done with Physic Ventures. Or it can establish an internal CVC fund, on or off the balance sheet. In all cases, money is not the primary issue. Rather, the company must be a strategic investor who is prepared to devote its non-financial resources—technology, brand, distribution, credibility, etc.—to help a start-up business succeed. By the same token, CVC investment value must be viewed in terms of strategic leverage more than near-term financial return. As such, the company must be prepared to be open and move quickly; that is, to operate like a VC and at the pace of a VC.

Applied Materials is one example of a company with a varied portfolio to such investments as synopsized from IDA's interview with Applied Materials' CTO Dr. Omkaram Nalamasu:

> Applied is embedded in an innovation ecosystem of customers, suppliers, academia, institutions and VCs. For example, AMAT will invest in VC deals to enable the development of a supplier, discipline or a nanotechnology application. Within this system AMAT must be able to recognize and seek ideas from others and collaborate and invest through strategic investments to disrupt the current market or enable a new product. New market developments come from both inside and outside. AMAT will incubate internal developments as investment in "inventures". External ideas are identified through relationships with academia, venture capitalists (VCs), and merger and acquisition investments. For these external and internal developments AMAT has a "structured vetting process" – using a score card on such criteria as synergy with strategic business plan, market opportunity, disruption potential, value-added in terms of providing a value chain technology for manufacturing or access to customers.

Examples of external ventures at Applied Materials are the acquisition of Italian firm Baccini for solar panel metallization and the acquisition of Precision Wiring, a Swiss firm. Baccini resulted in a thirty times revenue increase in three years, while Precision Wiring resulted in a ten times revenue increase in three years. Critically, the CTO and his technical staff play a major role in technology due diligence and assessing the prospects of such acquisitions. It is possible to make costly mistakes if they are not properly evaluated according to the vetting process. The company, according to Nalamasu "…must understand what the capabilities and potential are, what is different in what the acquisition would provide" and especially how it would affect it in terms of timing and capabilities. The guiding principle is how would the potential acquisition enable the market and the customer? As Dr. Nalamasu, put it, "Acquisition is the quickest pathway to solve customer problems."[18]

CVC works best when it is focused on defined areas and based on corporate and R&D strategy. Unilever, for instance, has set up several distinct VC funds targeted to specific technology areas and with defined investment period. That is, CVC funds work best when they are rifle shots, not shot guns. A strong, experienced, and dedicated team is essential to establish credibility and relationships with the broader VC community and university technology transfer offices, with an organizational structure that does not inhibit its activities but is still strongly attached to the corporation. Most importantly, the approval time for investment must be streamlined.

3. Corporate Entrepreneurship Organizations

Another new type of organization related to R&D are groups dedicated to corporate entrepreneurship; that is, the development of new businesses, not just new products or services.[19] Corporate entrepreneurship is related to corporate venturing, and the two efforts are often coordinated. The distinction is that corporate venturing deliberately leaves the external company management alone, often even if the company is eventually acquired. A corporate entrepreneurship organization seeks opportunities where the resulting new business depends on resources from the core business in order to reach its full potential and therefore tends to be more tightly linked to internal R&D. Corporate entrepreneurship may include fill in acquisitions as part of building a business that is intended, when ready, to become part of the corporate core.

In addition to overcoming technical challenges, bringing new businesses to fruition within large companies requires overcoming resistance within the corporation. Large corporations focus intensely on competencies that make the existing businesses competitive. New business development projects compete for corporate resources, but they do not fit with the existing businesses (and won't help them make this quarter's numbers) and hence tend to be ignored or under-resourced by BUs with other, better-understood opportunities for growing the existing business. Companies that have a strong history and culture supporting new business creation are able to make the link from R&D to businesses quickly and effectively. 3M is an example of a company in which researchers and business builders interact (and sometimes change roles) as a

[18] IDA interview with Dr. Omkaram Nalamasu, CTO, Applied Materials, July 7, 2011.

[19] The paragraphs on Corporate Entrepreneurship draw from Wolcott and Lippitz, 2010.

program develops. But changing a culture companywide requires a serious mandate from and direct engagement by the CEO and his or her lieutenants over an extended period of time.

Sometimes, rather than a corporate-wide focus, a special group is designated to build new businesses that leverage the company's internal capabilities. This group orchestrates the combination of internal R&D with external technology and partners. One type of external group is often dubbed a "skunk works," a term that has come to be understood as generically describing a separate R&D group with dedicated funding that is protected from the rest of the company.[20] Such separate organizations are often used in businesses that depend on sophisticated technology integration, where they focus on complex systems development and prototyping. Creating a separate organization aims to protect emerging projects from turf battles, to encourage cross-BU collaboration, to build potentially disruptive businesses, and to create pathways for executives to pursue careers outside their business units. Current versions of skunk works are more than privileged versions of central R&D. They are conscious of the difficulties that such separated organizations have traditionally had in bringing proven new businesses back into the mainstream company. So they are closely tied to corporate leadership and strategy, and they provide a great deal of support for the commercialization, transition, and scaling of new businesses.

Another model for encouraging corporate entrepreneurship is known as the Advocate Model.[21] In the Advocate Model, a company assigns organizational ownership for driving the creation of new businesses to a designated corporate-level group, but it intentionally provides the group with only a modest budget. Advocate organizations act as evangelists and innovation experts, facilitating corporate entrepreneurship in conjunction with business units, which must demonstrate their commitment to new business development by paying most of the bills.

D. Open Innovation

R&D and new product development partnerships with end-users, suppliers, competing firms, and research institutions are all increasingly commonplace. The literature estimates that "45 percent of innovations stem from external sources, with this figure as high as 90 percent in service industries."[22] The motivations for seeking external sources of innovation include:

- Lowering R&D costs
- Accessing a market that the firm does not understand well
- Obtaining technology knowledge that does not exist within the firm
- Obtaining component technologies with lower manufacturing cost or higher quality

[20] Lockheed set up the original skunk works, known as Advanced Development Projects, to lead the development of advanced projects during World War II. It continued quite successfully for many years. The skunk works got its name from a family of skunks that had nested near the facility.

[21] Wolcott and Lippitz, 2010.

[22] Cui et al., 2009.

- Focusing for strategic purposes on core competence and using non-firm sources for more ancillary technologies
- Avoiding internal bureaucracy and politics
- Upgrading the firm's internal R&D processes[23]

In particular, one frequently sees collaborative partnerships established between large, technology-driven firms such as Google, Microsoft, and Procter & Gamble and small, nimble businesses working in emerging technological areas. One sector where this has been prominent is pharmaceuticals: "In recent years there has been a much greater willingness by large pharmaceutical firms to engage much smaller biotechnology firms in marketing alliances, co-development programs, equity investments, etc., as new product successes from traditional chemical-based methods have diminished."[24]

One of the rationales underlying the open innovation model is the recognition that different types of partners provide differentiated value to the overall innovation process, as shown in the Figure 3 below.[25] What large technology-focused firms have determined is that by partnering with others who have differential knowledge and capabilities they achieve much better results in terms of developing and implementing new concepts and products. This partnering relationship is different than the classic "make or buy" decisions firms make in developing a product. In this case, the firm is deciding whether to buy a component or a subsystem from a supplier, while in open innovation approaches, the firm is partnering with others to develop a component, subsystem, or even an entire product. Open innovation is an interrelationship not just an acquisition. These two processes may overlap at times, especially as firms become more sophisticated and forward-looking in their supply-chain management. Perhaps, said differently, the future of make or buy for more astute firms may be open innovation.

As IBM specifically states, "25 years ago IBM's ethos was 'we can do it all.' Now, we don't want to do it all: We cannot afford it and there are a lot of smart people out there that we can and need to draw upon."[26] Because of this, IBM has committed to open innovation and R&D partnerships. Semiconductor Manufacturing Technology (SEMATECH)—the integrated circuit industry's manufacturing consortium, jointly funded by leading IC firms (including IBM) and the U.S. Department of Defense—is an early example of this philosophy. The current 3D IC program involving IBM is an open innovation program—fifteen companies are working in a consortium working with the National Institute for Standards and Technology (NIST). In reflection, IBM sees that its X-ray lithography is an example where IBM went on its own in a large-scale endeavor that failed because it could not attract the rest of the community. IBM was

[23] Ibid.

[24] Munsch, 2009.

[25] Cui et al., 2009.

[26] IDA interview with IBM executive, July 28, 2011.

too isolated from others in the industry and on its own could not effectively implement this extremely costly technology. Therefore, IBM's sees collaborative R&D working in strategic partnerships as a crucial strategy for its future. Thus, collaborative programs with exchange of ideas amongst "smart users" are seen as being of great importance.[27]

Open innovation has a range of definitions or implementations, ranging from a set of structured partnerships with specific suppliers or even customers to the outsourcing of technical, marketing, strategic, or other jobs to a large, often undefined group or community. Open innovation is often used in reference to connecting to external organizations known for a particular expertise through a formal agreement that addresses issues in intellectual property, process control, project milestones, management organization, etc. While this is not a new concept per se; it is simply external consultation or collaboration; the term *open* is used in this context to refer to a substantially increased degree of input sought from external firms and organizations, or input sought on a broader range of formal and informal issues.

Table 3.—Strengths and Weaknesses of Innovation Providers by Type.

Type	Key Areas of Usefulness	Innovation Stage	Main Outsourcing Motivation	Strengths	Weaknesses
Universities	General theory framework, prototyping	Raw ideas, early product development	Technology knowledge, cost	Access to novel ideas and features, low cost	Often little knowledge of market
Customers	Related needs, extended usage of existing products	Typically usability adaptations of mature technologies	Market access, strategic, cost	Knowledge of market requirements, new product concepts	Not for new categories, short-term orientation (want to use now)
Suppliers	Components, process innovation	Usually mature technologies or novel components	Production or technology knowledge, cost	Familiarity with firm's systems, expertise in related problems, efficient	Lack of novel ideas, might incur dependence
Competitors	Product benchmarking	Both precompetitive and mature technologies	Strategic, market access, cost	Knowledge of current market and technologies	Competitive threat, ownership conflicts
Start-ups	New product concepts, patented technologies	Emphasis on embryonic technologies	Technology knowledge, organizational learning, cost	Source of creativity and disruptive innovations	High market risk, commercialization gap, potential competitor

Source: Cui, et al., 2009

Figure 3. Strengths and Weaknesses of Innovation Providers by Type

One example of revised thinking regarding relationships with other firms is the change of focus made by IBM in the 1990s to go beyond and outside of IBM to link to others in its product development efforts—especially leading edge customers in various customer sectors. IBM assessed who were the best clients with most demanding needs. Who could IBM partner with to develop an understanding of their needs and create leading edge solutions? One early partner was L.L. Bean, who was exploring Internet selling in the 1990s. IBM partnered with Bean on

[27] Ibid.

developing its website. Other lead partners have included Bank of America, the New York Stock Exchange, and General Motors. This type of collaborative research is extremely important to IBM.[28]

Many corporations, such as Proctor & Gamble, have concluded that they cannot meet their growth objectives by simply spending more on R&D for less and less payoff, and have instead opted to leverage their research groups by softening the boundaries between internal labs and the external knowledge base.[29] "As [Procter & Gamble] studied outside sources of innovation, we estimated that for every P&G researcher there were 200 scientists or engineers elsewhere in the world who were just as good—a total of perhaps 1.5 million people whose talents we could potentially use."[30]

Assumptions underlying the concept of accessing a large, undefined external community for input on a particular technological challenge or research topic is that the issue is clearly defined, and that internal resources are not sufficient to answer it. Firms must identify their needs and subsequently ask: "What internal resources does the firm have to meet these needs? What additional resources are needed by the firm? How might the firm acquire the additional resources? Can they be developed in-house, purchased, or created via a partnership with an external source? What external sources might possess an adequate quantity and quality of the needed resources, based on the firm's present awareness of external sources? Does the firm have the skills to create and manage collaborative relationships with external sources?"[31]

Applied Materials is employing an open innovation approach in exploring the prospect of graphene-based semiconductor devices.[32] For Applied, the question is whether robust, replicable processes can be identified and developed for depositing graphene that can be cost competitive with projected alternative technologies. From its perspective, this new approach will require equipment to succeed, but there must be some relatively well-defined pathway identified to go from an invention into an innovation. Importantly Applied sees the *exploration* of the prospects of carbon electronics as primarily the job of academic research. To this end, it is both following developments in this area and also funding some academic research itself, for example through MIT's Graphene Center, as part of its investment of $10 million per year funding of university research.

This is an aspect of Applied's view of itself as being embedded in an innovation ecosystem of customers, suppliers, academia, institutions, and VCs. For example, as discussed above under corporate venturing, Applied will invest in VC deals to enable the development of a supplier,

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[28] Ibid.

[29] Huston and Sakkab, 2006.

[30] Ibid.

[31] Slowinski and Sagal, 2010.

[32] IDA interview with Applied Materials executive, July 7, 2011.

discipline, or a nanotechnology application. Within this system it must be able to recognize and seek ideas from others and collaborate and invest through *strategic investments* to disrupt the current market or enable a new product. New market developments come from both inside and outside. Applied will incubate internal developments as investment in "inventures." External ideas are identified through relationships with academia, VCs, and merger and acquisition investments. For these external and internal developments the company has a structured vetting process—using a score card on such criteria as synergy with a strategic business plan, market opportunity, disruption potential, value added in terms of providing a value chain technology for manufacturing or access to customers.

1. Technology Scouting

Another mechanism for identifying and linking to external sources of ideas and capabilities is an explicitly chartered technology scouting organization. One example of this is the Boeing Technology Scouting Group.[33] BTSG performs a type of open innovation, playing a matchmaking role across the enterprise between external technology sources and internal business needs. BTSG works with the BUs to understand their business environment and needs and to identify gaps in their capabilities for which tech scouts can seek outside solutions. They spend about half their time understanding what BUs need and the other half finding and vetting external technologies (referrals). BTSG is one of several technology scouting teams within Boeing, but it is the only one that uses an external network of referral agents—including venture capital firms, economic trade organizations, investment arms of large corporations, and university technology transfer offices—to find new and indirect value for the enterprise, usually in adjacent industries such as construction or energy. As such, it complements networking and scouting efforts by BUs that tend to focus on traditional aerospace suppliers.

Money-for-information is not sufficient to ensure the success of a scouting network. Technology scouting relies on formal and informal information sources, including the personal networks of the scouts. BTSG scouts tend to be lateral thinkers, knowledgeable in science and technology, respected inside the company, cross disciplinary, and imaginative.

2. Social-Sourced Innovation

While corporate-driven processes looking for innovation are usefully employed, at the extreme end of the open innovation spectrum is what might be termed "social-sourced" innovation. This approach to open innovation is a highly undirected hands-off and thus a more unpredictable approach to idea collection and problem solving, akin to "crowdsourcing." Companies have implemented this notion in various ways.

One approach is the fostering and use of outside agencies that gather experts from across industries and sectors, such as InnoCentive. InnoCentive is a company founded with seed

[33] IDA interview with Boeing executive, July 27, 2011.

funding from Eli Lilly that collects challenges from journals, government agencies, private firms, and other sources and posts them on its web site, along with the reward for solving each challenge.[34] Users can register and contribute freely. InnoCentive's expert network relies on "a crowd of extremely talented scientists with highly specific skills. To attract them, InnoCentive recruits at universities, where young, smart minds have not yet entered the workforce."[35]

Shell has been an innovator in social-sourced innovation with its GameChanger program.

Shell created GameChanger, a separate process that could be used to set different priorities and establish social mechanisms to safely hear out crazy ideas, as well as assess them using suitable models and measures. GameChanger was designed as a proof-of-concept process—i.e., only for the early stages of innovation. An idea's merit is discovered by working with it, not just analyzing it. In this way, experience, not assumptions grounded in orthodoxy, drives later decisions. Because GameChanger focuses on high-uncertainty projects, the process was designed to be dynamic and flexible so that it could both amplify successes and truncate failures early.

GameChanger is an autonomous team of people who invest a separate pool of funds amounting to roughly 5 to 10 percent of the total R&D budget using a simple, fit-for-purpose, real-time process. Successful projects graduate for further development under a core R&D program, a license to another firm, or a new venture company.[36]

However, once this community has been reached, mutual interest can be difficult to establish, especially with the existing R&D establishment of the company. "Tapping into the creative thinking of inventors and others on the outside would require massive operational changes. We needed to move the company's attitude from resistance to innovations 'not invented here' to enthusiasm for those 'proudly found elsewhere.'"[37] Professor Edward B. Roberts of Massachusetts Institute of Technology's (MIT) Sloan School of Management notes, "'Open Innovation' at the community level has moved us in several fields far beyond the more limited assumptions of external user contributions. The resulting challenge is that now invention and innovation must be managed across organizations rather than just inside of them, as well as around the world."[38]

Moreover, one of the challenges of the crowdsourced social innovation model is connecting organizational work to the *right* people within the larger population. Reaching out to too large a community can decrease the signal-to-noise and thereby increase the amount of time that passes before connections with experts are established and useful input can be examined and recommended. For businesses working on tight budgets or short timelines, the delay can be fatal.

[34] Innocentive, http://www.innocentive.com.

[35] Hempel, 2006.

[36] Cosner, 2008.

[37] Huston and Sakkab, 2006.

[38] Roberts, 2007.

Options include reaching out to subcommunities through targeted advertising, utilizing an already-existent network of experts or personal contacts, or capturing the attention of the broader media as a start-up or entrepreneur often seeks to do.

Not only do useful external submissions need to be recognized and promoted, but also the "crowd" needs to clearly perceive an incentive to participate in the first place.[39] In optimal circumstances, crowdsourcing permits talented individuals to contribute their expertise to exciting projects in which they would not otherwise participate. Financial costs to the company and intellectual property hurdles can both be lowered by the contributors' interest in the issue, desire to provide expertise or be recognized, etc.

A different form of open innovation relates not to the acquisition and filtering of input from an open community of supposed experts, but rather to creating an open, frequently networked *platform* that empowers the user to create their own products, services, systems, and tools. In this context, openness refers to "the easing of restrictions on the use, development, and commercialization of a technology."[40] The open platform model involves selling (or freely spreading) a platform for user activity (system and/or component interaction) that is flexible, accessible/scalable, and capable of evolving under the limited or full control of a large community of creators and users. In fact, these communities frequently overlap. Examples include Google's Android mobile operating system, the Linux computer operating system, and "wikis." Thus,

> A critical dimension of a platform is its degree of openness. A closed platform is restricted to a firm and its network of certified subcontractors. Innovation in closed platforms thus tends to be highly controlled and directed by technology roadmaps. An open platform, on the other hand, allows independent third parties to create and capture value around its common core, without the need for prior contractual agreements.[41]

In this system, technical capabilities, customer needs, and markets themselves co-evolve with platform and module iterations. One inherent risk is that user decisions directly impact the generation of modules, components, and services—the utility of the platform—as well as the adoption by other users. A poorly designed platform for the generation of user content simply does not survive, and any platform generally requires extensive firm resources to develop and spread, often profitlessly.[42] Once an open platform does take off, the degree of openness directly affects its profitability. One author writes, "opening has the potential to build momentum behind a technology, but could leave its creator with little control or ability to appropriate value."[43]

[39] Hempel, 2006.

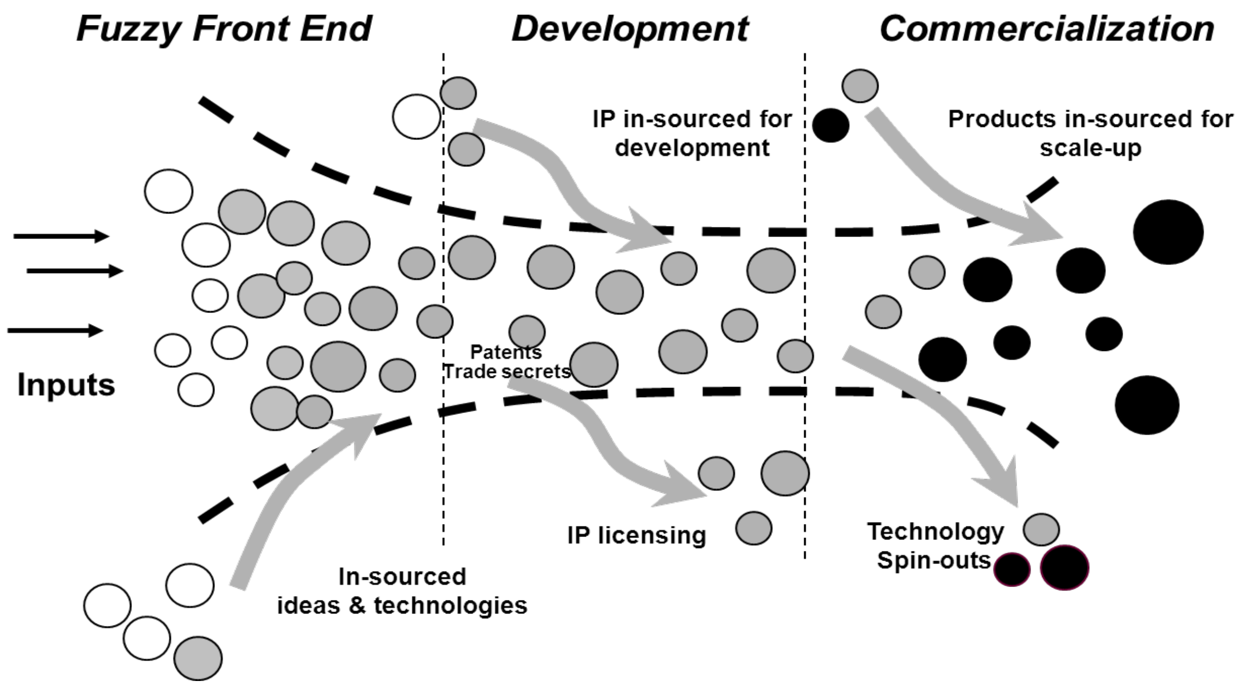
[40] Boudreau, 2010.

[41] Miller and Olleros, 2008.

[42] Ibid.

[43] Boudreau, 2010.

Open platforms have the capacity to be highly disruptive, as they can upset an established value chain by drawing value from nontraditional areas (for instance, ad revenue) and thereby providing products and services for free or at a steep discount.



Source: M. Docherty, Venture2 Inc., based on concepts by Henry Chesbrough's Open Innovation, 2003

Figure 4. Open Innovation Takes Different Forms at Each Stage of Concept Development

3. How to Make Open Innovation Work and How to Evaluate It

Open innovation is not simply outsourcing. Rather it is an organized, structured process for looking outside for ideas and then developing them using a mix of internal and external capabilities. Many firms see this as superior to trying to innovate only through central labs—but also many firms, such as Applied Materials, Boeing, Exxon Mobil, GE, Intel, IBM, and P&G, see the need maintain robust labs to exploit and integrate open innovation prospects.

Key issues firms face in open innovation are:

- How to implement open innovation without stifling internal R&D?
- How to best access possible contributions of outside partners?

From the interviews and literature, the IDA study team identified the following emerging practices in collaboration and open innovation:

- All firms interviewed stressed the crucial role of both upstream and downstream partnering (customers and suppliers).

- Universities are being increasingly turned to for science and advanced concepts.
- Vertical and horizontal consortia are becoming standard practice.
- Open innovation approaches are becoming almost universally adopted and adapted.
- A key role for the CTO is managing and linking open innovation into the overall R&D process.

Also two important points emerged in the interviews concerning the role of government in the partnering across industry and between firms and the government as well as universities and other research centers:

- The role of government is seen as essential in fostering S&T collaboration,

but

- Other governments are increasingly funding high-risk S&T collaboration.

It is beyond the scope of this study to delve into this emergent phenomenon, but it is certainly the case that leading firms see that developing and supporting the innovation ecosystem that facilitates their ability to "make big bets" is a crucial role of the national government as well as specific regions. As firms become more open and see their futures depending on their ability to interconnect with suppliers and customers, the infrastructure support for collaboration, including funding to support it, becomes increasingly important. Several firms noted the important role that they saw SEMATECH playing as a supporter of inter-firm and supplier infrastructure collaboration in reinvigorating U.S. semiconductor manufacturing. The role of major investments by foreign governments, as well as very attractive policies for locating production and research facilities, in addition to burgeoning market prospects were identified as important factors that lead to firms looking outside the United States to conduct their R&D as well as manufacturing.

3. R&D Portfolio Planning and Assessment

Leading firms that invest substantially in R&D have well defined and assiduously monitored assessment processes. Most of the companies explicitly start with the definition of the value of R&D in their corporate strategy—which is usually expressed in terms of how and in what way R&D contributes to the firm's ability to effectively and competitively introduce and produce new products. They also define targets for R&D, such as the creation of new products that generate a defined percentage of total corporate revenues in future years. In other words, R&D is about *results* and therefore it should be measured more in terms of impacts, not inputs and the internal R&D activities themselves.

The companies IDA interviewed and the research management literature focus a great deal on developing a portfolio mix and managing the portfolio relative to explicitly defined (deliberated and negotiated) strategic goals. Portfolio development and assessment is a strategic enterprise usually under the CTO but with high-level business unit involvement. Portfolios may be defined in many ways, including 1) distribution of projects across businesses; 2) allocation to single businesses versus enabling or cross cutting platform technologies; 3) internal versus external capabilities; and (4) allocation for potentially new businesses versus current businesses.

A. Distribution of Projects Across Businesses

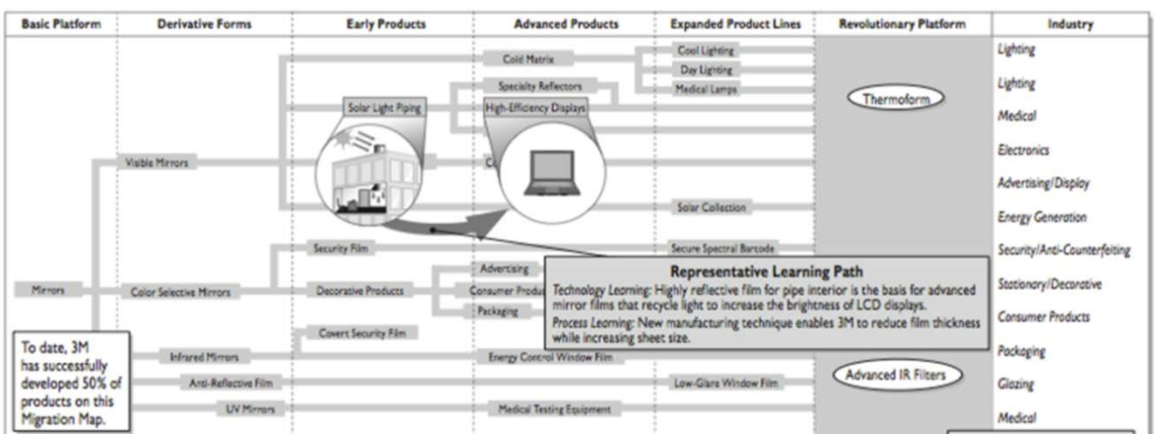
Resource allocation decisions engender the most significant political fights in multi-division companies. Investments in R&D, capital expenditures, and other corporate-controlled resources are usually divided up based on power positions rather than rational allocations. Just as individual states in the United States keep track of how much money they send to Washington, DC, versus how much they receive back in federal allocations, corporate business units—which often fund central R&D via an internal tax—want to receive fair allocations of the R&D conducted. The politically expedient decision in many firms is to allocate corporate resources roughly proportional to the revenues each unit brings in.

However, leading firms understand that proportional allocation across business units is generally sub-optimal. Some business may be small but represent future growth engines, while others may dominate corporate revenues but are fading businesses. The latter are often "cash cows" that throw off significant profits and should be nurtured to extract maximum cash flow. Those profits are then plowed into future growth businesses that often represent a replacement for the cash cow business. Clearly, political courage and strong leadership are required to fund smaller or even fledgling businesses at the expense of cash cows.

B. Enabling or Cross-cutting Platform Technologies

The case of Kraft Foods is illustrative of how companies define and allocate R&D funding to projects that support multiple businesses. As part of a re-organization in the mid-2000s—prior to the recent split between North American Grocery business and their foreign and emerging markets businesses—Kraft distributed much of its central R&D resources out to its business units. In 2009, concerned that insufficient attention was being given to long-term, cross-business R&D, Kraft established a Global Technology Council (GTC) to identify, assess, and recommend Breakthrough Technology platforms for investment with potential to generate significant revenue for new or existing Kraft businesses, or address enterprise-level risks. A key objective of the GTC is to align senior executives' across the enterprise around long-term investments in potential breakthrough technologies with implications across Kraft businesses.[44]

3M illustrates another approach to identification and incubation of long-term, cross-business technology platforms.[45] In the mid-2000s, 3M observed that many of its greatest successes came from applying advances in core technologies across products lines and into new markets, often in ways that were not obvious at the beginning of the R&D process. For example, an advanced prism reflectivity technology, developed and applied initially for overhead projector lenses in 1965, was later applied to develop diamond grade sheeting for road signs, the lessons from which led to a breakthrough in brightness enhancing films for liquid crystal display (LCD) screens. Figure 5 represents the technology migration path.



Source: RTEC 2009

Figure 5. Migration Map for 3M Lens Technology, Originally Applied to Overhead Projectors

Today, when 3M research discovers a new technology with numerous potential applications, it creates a Technology Migration Map that identifies possible pathways from

[44] Walcott and Lippitz, 2010.

[45] Example drawn from Research & Technology Executive Council, "Capturing Strategic Value from Incremental Innovation," 2009.

initial, near-term opportunities out to long-term, stretch goals. Each product on a Migration Map provides strategic technology, supply chain, and market learning that benefits the development of future products, while also providing near-term revenues to fund continuing R&D. Returning to the previous example, the development of reflective film for solar light piping taught 3M about manufacturing processes that made possible the commercial development of thin mirror films that were applied in LCDs.

A Migration Map is different from a roadmap, such as those that Intel uses in the integrated circuit industry. The IC roadmap is aimed at coordinating the development cadence across the IC supply chain toward agreed performance objectives. A Migration Map represents multiple potential directions for 3M and its suppliers. A product on the Map is not necessarily developed. Rather, as 3M learns at each stage, it identifies the development paths that will provide the strongest market position and hence accelerate learning.

Developing a Migration Map requires intensive attention for several months by a diverse team of top researchers, marketers, intellectual property (IP), supply chain, and manufacturing experts, called New Business Architecting Teams. They undertake the following steps:[46]

> **Revolutionary Opportunity Identification**
>
> 3M identifies capabilities that differentiate it from competitors and that could be extended to form the basis for future revolutionary platforms.
>
> **Technology-Process-Application Mapping**
>
> 3M then assembles a team to generate ideas for products that would leverage the existing capabilities and build the future platform. The team uses a set of worksheet tools to develop a broad set of interrelated technology, process, and product concepts.
>
> **Value Chain Expansion**
>
> Recognizing that initial product concepts may assume suboptimal business models, the team considers alternative value chain positions to identify the strongest potential applications.
>
> **Strategic Concept Sequencing**
>
> 3M organizes the most promising product concepts into Migration Maps based on the potential for differentiation, technical and market readiness, and their relationships to other potential products. The team identifies the development sequences that maximize future options.
>
> **Strategic Contribution Assessment**
>
> Following construction of the Migration Map, the team prioritizes near-term product investments based in part on their long-term impact. The team assigns R&D resources to

[46] Quoted from RTEC, 2009, 52.

> products based on a balance of rigorously assessed strategic value—the technology, process, and market learning provided to future products on the Map—and traditional financial value.

While there are many opportunities for such cross-organizational investments in DOD, the dispersed nature of DOD's current R&D resource allocation process amongst the military departments limits the utility of this approach.

C. Internal Versus External R&D

Section 2.D on Open Innovation described various ways that companies are seeking to supplement and leverage internal R&D with external scientific and technical capabilities. P&G's Connect+Develop strategy was born out of recognition that "only about 15% of P&G's innovations were meeting revenue and profit targets."[47] The C+D approach is focused on stimulating innovation and encouraging researchers to search for technologies outside of P&G. To track this, P&G revamped and integrated its innovation and strategy assessments, which had previously been separate activities. "Now the CEO, CTO, and CFO explicitly link company, business, and innovation strategies." Included in this assessment is an examination of the pipeline of growth opportunities against growth goals over seven to ten years. This assessment includes a clear development of an investment portfolio with a mix of innovation types needed to deliver the growth of the business area.

D. Allocation for Potentially New Businesses

Most firms have adapted the three horizon concept of nested portfolios, including Applied Materials, IBM, Intel, P&G, and GE. The concept of "3 Horizons," introduced in the book *The Alchemy of Growth*,[48] is also essential in effectively separating and managing different product or technology development tracks. This concept refers to three levels of business establishment, and explains the appropriate management procedures for each level. H1 businesses are established and profitable businesses, H2 businesses are rapidly on the rise, and H3 are new and emerging businesses, possibly focused on an area of unknown value. Each type of business operates with different short-term objectives and requires different management approaches: H1 businesses could be managed according to traditional budgeting systems. H2 businesses, by comparison, require "disciplined risk taking and significant resource commitments in order to scale up quickly. Leaders should therefore be judged on revenue growth and market-segment share gains."[49] H3 businesses need "visionaries and champions, leaders who could think out of the box and create new strategies and business models in the face of ambiguous, evolving

[47] Brown and Anthony, 2011, 64–72.

[48] Baghai, Coley and White, 1999.

[49] Garvin and Levesque, 2005.

environments. They were best measured on project-based milestones that showed their progress in converting grand ideas into workable businesses."[50]

Applied Materials' definition of horizons H1, H2, H3 is one example.[51]

- H1 is driven primarily by the business units and is mostly roadmap focused and is customer and collaboration driven. SEMATECH, ITRS and other consortia are important in this process. The roadmap identifies key challenges through a "stoplight" chart. This is development that is highly customer focused in the N+1 and N+2 timeframes.
- H2 is primarily corporate research aimed at building on developments identified in H3 that support identified customer needs or present tangible prospects of new products or new market entry. Applied Materials uses a combination of Process Portfolio Analysis and Product Lifecycle Analyses (gated investment discipline for product development) for determining H2 R&D priorities. Applied seeks to have 25 percent of its revenue to result from H2 R&D within five years—thus $2.5 billion of $10 billion revenues are derived from H2 R&D.
- H3 is exploratory R&D aimed at opportunities in new or adjacent markets, potential disruptions in the core market, and foundational technologies. AMAT allocates about 15–20 percent of R&D to H3 projects.

R&D needs to be managed differently within these three horizons, with risk thresholds appropriate to the level of uncertainties—with failure tolerated (even encouraged) at the H3 "fuzzy front-end" and essentially no failure tolerated in H1 product development and launch. The skunk works organizations described earlier are often the home of radical innovation experimentation in H3. Intel is a good example of zero-tolerance of risk and failure at the H1 implementation stage; they have an elaborate and carefully orchestrated "tick-tock" product-process implementation approach. Intel and other firms see H2 projects as the time where the risk is taken out progressively at each stage-gate milestone within this stage of development.

The exact timeframes and internal processes for H1, H2, and H3 vary in different industries and business areas. Intel functions within the lock-step dynamic of Moore's Law with two-year product and process windows. Its R&D process is gauged within this roadmap of successive generations of products and processes. Where there are gaps in capabilities to meet roadmap needs, these are identified to the extent possible upfront in the roadmap process so that separate research and development can focus on these and they can be matured for insertion when needed.

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[50] Ibid.

[51] From interview with Applied Materials, 2011. This concept draws explicitly on Geoffrey Moore (2007) "Focus on the Middle Term," *Harvard Business Review*, July-August, 84–90, in turn drawing upon the prior McKinsey work cited above.

Examples include the “tri-gate” 3D transistor and hi-K dielectrics, which were identified as means to address identified technical issues with gate and channel current leakage.[52]

GE with its highly varied businesses has to be attentive to very different time windows. Thus the management planning and assessment of research for a new turbine engine is very different from the energy components group. Moreover, it has different expectations for a new thrust into energy-efficiency devices (photovoltaics or energy-monitoring electronics) than it does for its longstanding locomotive-transportation business.[53]

The adoption of the “3 Horizons” framework and a renewed focus on understanding and nurturing “Emerging Business Opportunities (EBO)” spurred a revolution in business management strategy within IBM.[54] After senior management noticed that emerging business revenue was falling shorter and shorter each year, an EBO study team was formed, which “concluded that IBM had one management system, designed for large, established businesses, and was using it unsuccessfully to manage its new businesses as well.”[55] It found that managers harbored distrust of intuition and shied away from embryonic or undefined markets, preferring to rely solely on factual financial analysis even if a market were too small to truly support it. In addition, IBM lacked established disciplines for selecting, experimenting, sponsoring, funding, monitoring, and terminating new growth businesses, and the study team noted a general absence of adequate entrepreneurial leadership.[56]

The company responded to these inadequacies by defining and classifying existing IBM projects as H1, H2, and H3, establishing seasoned senior managers as the EBO project managers, and building an explicit EBO management system that is driven from a central unit and led by a senior executive, but *also* gives authority and accountability to line management. This hybrid line-corporate management structure was created in order to leverage divisional infrastructure and improve the odds of successfully transitioning H2 business management into specific divisions down the road, but at the same time to avoid the short-term strategic initiatives, perpetual day-to-day crises, inter-divisional competition, and stovepipe of the line organizations. EBO manager reviews focused on milestones rather than financial data. However, expense meetings and milestone meetings were held alongside one another, in order to appropriately align project funding and task prioritization.

By 2003—four years after these findings were reported at IBM—several success stories had already come out of IBM’s new EBO system, including two emerging businesses each generating over $1 billion annually. By then, the greatest challenge to the EBO managers was

[52] IDA interviews with Intel executives, July 11–13, 2011.

[53] IDA interview with GE executive, August 26, 2011.

[54] Garvin and Levesque, 2005.

[55] Ibid.

[56] Ibid.

moving businesses from H3 to H2 and from H2 to H1, and then scaling up the EBO program to include more businesses. With senior management already sustaining and supporting current projects that matured very slowly, there was minimal managerial capacity to focus on new businesses. IBM's Senior Vice President of Corporate Strategy noted, "What really worried me was how exhausting it was to support 18 EBOs when I believed we needed 180 of them to really grow this company."[57] As discussed in the section on open innovation, one approach is to spin out selected projects to subsidiary companies or external partners.

E. Portfolio Assessment and Management Practices

Project portfolio management refers to the management of a group of related projects within the company, and its focus is on maximizing the value of the existing portfolio through tactical management of resources. In innovation portfolio management, executives develop a strategy to select and develop new concepts, connecting them eventually to *project portfolios*. The innovation portfolio is similar to what others have called an innovation roadmap. Regarding the purpose of the innovation portfolio, MIT's Roberts emphasizes: "senior executives need to provide linkage between their own insights to corporate vision and direction and tie them to the choices and priorities of major undertakings."[58] However, while the project portfolio is a tightly managed process designed to efficiently deliver identified products or results, involvement in the innovation portfolio design process is not necessarily exclusive to management. "In terms of the portfolio control system architecture, the innovation portfolio is a positive feed-forward, open-loop system for evolution and discovery; the project portfolio is a negative-feedback, closed-loop system for delivery."[59] Examples exist of tight, centralized design and management of company-wide innovation portfolios—the most notable being Apple, but most of the high-technology or highly innovative firms the IDA study team examined favored a more open and collaborative process of ideation and concept maturation, opting for increasingly tight budgetary and strategic oversight during phases of actual product development.[60]

Assisting R&D leaders in their approaches to portfolio management are a variety of best practices from the literature, which recall the strategic R&D management principles discussed earlier in this paper:

- *Link project objectives to business strategy*: "Development projects are aligned with business strategy, and there is the right balance of projects in the portfolio; strong portfolios contain high-value projects with few low-value, trivial projects."[61]

[57] Ibid.

[58] Roberts, 2007.

[59] Mathews, 2009.

[60] Kahney, 2010.

[61] Cooper and Edgett, 2010, 38.

- *Take risks, but also manage them*: Taking risks means "invest[ing] resources in…novel or emerging" areas "[62] Managing risks means "close future gaps before they open."[63] Investing in new areas "give[s] an organization access to knowledge and insights that will help to position it for the future."[64]
- *Invest in the long term*: "[I]f we cut key profit drivers today, tomorrow's earnings will never appear….[l]ong-term programs require continuous investment to achieve milestones" that will pay off in the long run.[65]
- *Use strategic bucketing/project prioritization*: There are differing rationales for using strategic buckets. They "help management define where the development dollars should go, by project type, by market, by geography, or by product area (as well as) earmarking specific amounts to 'new products' or to 'platform developments'." [66] They "[help] firms to achieve a balance between protection of their current position and the creation of future options [and ensure] the apples-to-apples comparison of opportunities."[67] They help firms "kill the bottom programs…It is never a good strategy to sacrifice the top programs in order to keep the bottom performers on life support."[68]
- *Consider how external trends will influence projects value:* "(map) the market and business trends and drivers that influence the prioritized value opportunities ... social, economic, environmental, technological and political drivers, knowledge about potential customer needs and competitors, as well as the milestones and goals of the technology."[69]
- *Communicate the value of innovation*: "Communication programs ensure that: 1) all employees know their precise role in the innovation programs; 2) the link between innovation and business value of the organization is clearly articulated; 3) there is clear communication of what exactly the innovation process is and how employees should proceed in terms of leveraging ideas; and 4) rewards and recognition for innovation are clearly communicated so as to energize the organization." Communicating the value of innovation can take many forms, including in-house research conference-style events,

[62] Braganza et al., 2009, 53.

[63] Terwiesch and Ulrich, 2008, 31.

[64] Braganza et al., 2009, 53.

[65] Banholzer, 2010, 24–25.

[66] Cooper and Edgett, 2010, 38, 39.

[67] Terwiesch and Ulrich, 2008, 33–34.

[68] Banholzer, 2010, 26–27.

[69] Dissel et al., 2009, 51.

such as TechCon, which Hewlett-Packard holds every year and which is also an incubator for "future innovative efforts."[70]

- *Be customer-focused*: "Thoroughly understand[ing] the customer and what he or she will pay for."[71] The IDA study expands on this topic below.
- *Have a roadmap:* Roadmaps "can be used to support dialogue with [the project team], senior management[,] and other stakeholders."[72] A strategic roadmap is "an effective way to plot a series of major initiatives in the attack plan" and is a representation of "a management group's view of how to get where they want to go or achieve a desired architecture." In such a roadmap, "senior management maps out the major new product initiatives required in order to succeed in each strategic arena, and their timing."[73] Value roadmaps "are a way to explore and improve the value of technology projects at an early stage, linking current investments and decisions to longer-term business outcomes."[74]
- *Have leadership involvement and buy-in*: "The role of a CTO is to influence the key decision makers …. to ensure that top projects are protected, even if they are longer range."[75] Additionally, managers should "learn the innovation process, the need for it, and the ways to encourage innovation in their organization."[76]
- *Manage talent well and encourage innovation:* "Companies that prosper and grow are those that listen to, engage, and guide their employees." For example, at John Deere there is a "culture of respect" and "an environment where individuals can feel comfortable challenging the status quo, voicing their opinions and seeking ways to help each other be successful….this kind of culture breeds trust. And trust helps open minds, engages people, and ultimately fosters innovation."[77] At Hewlett-Packard, "[t]he role of the manager is to make sure that the outputs generated by [employees, who are not interfered with] can be commercialized." 3M "allow[s]…employees to spend time working on their innovations and [builds] [s]lack…into organizational plans, [which creates] room for reflection and thinking."[78]

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[70] Braganza et al., 2009, 54.

[71] Lane, 2008, 26.

[72] Dissel et al., 2009, 52.

[73] Cooper and Edgett, 2002b, 40.

[74] Dissel et al., 2009, 52.

[75] Banholzer, 2010, 27.

[76] Braganza et al., 2009, 51.

[77] Lane, 2008, 29.

[78] Braganza et al., 2009, 53–55.

1. Customer Focus

One of the guiding practices urged on firms for laying out their R&D portfolios is to be *customer-focused*: "Thoroughly understand[ing] the customer and what he or she will pay for." Thus, one major change in corporate R&D over the past has been an increasing focus on the customer and product. This is exemplified by IBM refocusing its research division to have "an explicit customer focus, where "customers' are both in the marketplace and internal (those who develop the innovations into product results."[79] From this standpoint, IBM still conducts leading-edge scientific research, but to be supported and sustained it is now an imperative that this research be linked to clearly defined product and customer needs. Significant funding for IBM research now comes from the business units and the businesses work more closely with the researchers because of their investment of these funds. One example of this closer relationship is IBM's "First of a Kind" program that assigns an IBM research scientist to a carefully selected customer *outside of IBM* to develop a solution to that customer's problem. This then expanded into IBM's Emerging Business Opportunities program discussed in the section on open innovation.[80]

With this focus, customer input is increasingly valued at earlier and earlier stages of product development. Based on the literature, these trends reflect an array of activities across different innovative high-technology organizations. As exemplified by Proctor and Gamble, companies will use a broad range of consumer research methods to ascertain or anticipate customer interests including consumer satisfaction surveys, focus groups, quantitative collection and analysis of data that reflects consumer information and activities, and consumer behavior research and observation.[81] Some firms use consumer satisfaction surveys directly, or interview and interact heavily with customers about what they want or need in a developing product. When Raytheon's Homeland Security business won its first large contract, it demonstrated its commitment to user-driven design and product development through the construction of a product development and demonstration facility, "where customers could work and interact with homeland security systems architects and developers. Lessons were learned in both the sales and technical areas."[82]

Methods such as consumer satisfaction surveys and use of focus groups are historically established—many were pioneered decades ago by advertising departments and polling groups. Others use special guided interviews and other qualitative research and observational methods to analyze consumer behavior in less traditional ways. For most innovative firms, qualitative analytical techniques were used more than quantitative methods.[83] As an example of

[79] Van Atta et al., 2003, B-8.

[80] Frederich and Andrews, 2008.

[81] Brown and Anthony, 2011.

[82] Meyer and Poza, 2009.

[83] Cotterman et al., 2009; Emery, 2010.

experimental qualitative user research, during the design of its new 787 Dreamliner, while Boeing employed traditional product evaluation surveys, it also developed two proprietary data-gathering techniques called *archetype discovery* and *idealized design*. These were part of a "quest to delve deeper into the mind of the passenger."[84] In archetype discovery, Boeing examined "participants' earliest experiences in the subject area being studied. In exploring what people seek from the air travel experience, archetype discovery unveiled key psychological and emotional components common to many airplane passengers."[85] While archetype discovery focuses on the unarticulated emotional components of an experience, in idealized design, participants were asked to describe their "ideal" flying experience as limited by the use of currently available technologies and realistic operational feasibility. The feedback from these methods helped inspire the carefully modulated interior space of the Dreamliner, which drew inspiration from church architecture.

Apple is an extreme example of a company that is product development and design focused, which lowers R&D costs dramatically, and generally features a very small team of carefully selected engineers and designers[86] (In this regard, Apple is a product-focused company that seeks to anticipate and create customer interest rather than using market analysis or survey approaches.) In support of the centralized, management-driven product development process employed at Apple, John Scully notes that, "[Jobs] believed that showing someone a calculator, for example, would not give them any indication as to where the computer was going to go because it was just too big a leap."[87] Mr. Jobs is known for involving himself in every aspect of the design of Apple products, even "the experience of opening the box."[88] In a sense, Apple is *forecasting* user preferences or needs.

However, this highly individualized practice can be worrisome because it offers less room for oversight and review—those who perform the forecasting may not have a realistic understanding of the firm's technological capacity or of the consumer. Thus most firms appear to purposely avoid highly centralized ideation regarding both product development and the examination of the consumer's expectations and experiences, and instead employ such techniques as multidisciplinary workshops or company-wide (and even externalized or "open") idea generation practices including user surveys and interviews.

While Apple appears to have a unique approach to anticipating customer needs and interest, other firms have developed active research efforts in assessing the "user experience" and anticipating potential user interests. Intel has even employed ethnographers, anthropologists, and psychologists to help guide the research process. As one anthropologist at Intel noted, they are

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[84] Emery, 2010.

[85] Ibid.

[86] Kahney, 2010.

[87] Ibid.

[88] Ibid.

hired in order to, "think about how understanding [the user's] everyday practices might generate new forms of technology… Engineering tends to start with what is technologically possible. Part of [an anthropologist at Intel's] job is about how you talk about experiences as a starting point instead."[89]

One variable that emerges among the examples studied is *who* is formulating the ideas. With traditional customer surveys, it is often marketing analysts who collect and examine the data, which can be quantitatively or qualitatively gathered from customers. As previously mentioned, at Apple this is a small group of executives, technologists, and design experts. Many firms, such as Boeing and Exxon-Mobil, use technically savvy employees to serve as brokers between customers and engineers and/or research scientists. At Raytheon, engineers and potential consumers communicate with one another on both user experience and technological issues. Across the board, the product development portfolio increasingly is tailored to anticipating the customer by employing technological progress to shape market need.

[89] Webb, 2011, http://www.newscientist.com/blogs/culturelab/2011/05/intel-anthropologist-fieldwork-with-the-silicon-tribe.html.

4. R&D Project Management

A key takeaway from both the literature and interviews is that R&D needs to be organized and managed in different ways for different stages.[90] Thus, the relevant managerial question for early-stage opportunity creation is how to generate more and better targets? Which people, which structures, and which strategies can be employed toward more effective idea generation for these objectives? Later, as a technology is ready to be transitioned and scaled into commercialization, the focus is on deployment success with tight control. Commercial development usually takes as long as the several earlier stages combined and requires more resources than most of the other stages together. That is the reason for tight financial standards being properly applied immediately prior to a project's entry to this stage.

Richard Leifer and his colleagues in the 2000 book *Radical Innovation* suggest that early stage idea generation benefits from two types of people:[91] 1) "Hunters," who actively seek out ideas with application potential, and 2) "Gatherers," who understand strategic needs and are poised to recognize and technically validate promising new ideas. "Hunters are people with "technical training," but they are more likely to be experienced in marketing or business development" (in an industrial environment) or in high-level systems management (in government). "Perhaps more importantly, a successful hunter knows how to articulate the opportunity in compelling terms that gain the attention of higher management—something that few bench scientists are skilled at doing." Gatherers, on the other hand, "have the technical sophistication to assess what they encounter. In addition, their life experiences have engendered a certain…awareness of markets and social and scientific trends…first-line and midlevel research managers and senior scientists… (often play)…the role of gatherer."[92]

People with the disposition and orientation to be hunters or gatherers can be hard to find. To make such technology search champions most effective, leading organizations systematically pursue needs discovery and definition and continuous technology monitoring and assessment, including regular outreach in important technology communities, and provide professional support for project and process management (see discussion of open innovation in Chapter 2, section D). Market needs monitoring and technology scouting foment innovative concepts that may be developed into new businesses, through a systematic (but flexible) stage-gate process.

[90] Roberts, 2007.

[91] Leifer et al., 2000.

[92] Ibid.

A. Project Evaluation: The Stage-gate Process

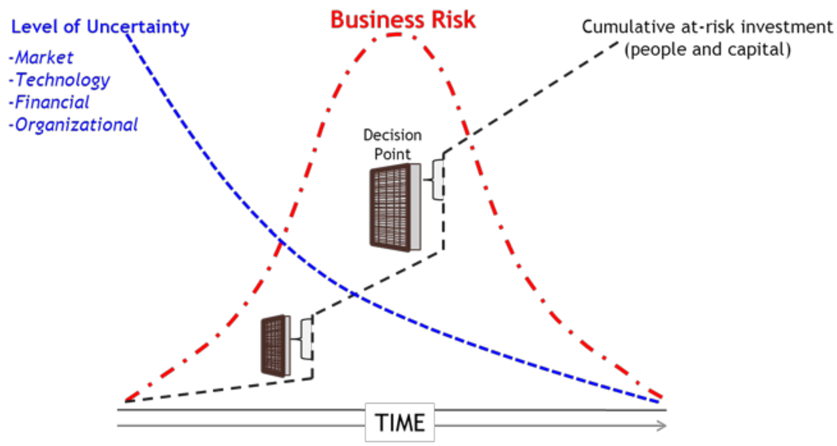
The R&D management literature and the interviews IDA conducted with industry executives show that most technology-based firms use some sort of stage-gate process in their R&D management.[93] From this review, some specific lessons and perspectives come to the fore:

- The key question is making the stage-gate process stick. That is, how to use it to actually stop projects and programs?
- The level to employ the stage-gate process and who to involve in it depends largely on technology horizon and strategic importance of the technology—it should not be employed as a "one-size fits all" cookie-cutter approach.
- Detailed analyses must underlie the stage-gate assessment: Are milestones and performance metrics being met? Are there identifiable impediments to success? Has the product / market environment changed?

Leading firms use rigorous, but specifically designed stage-gate processes to manage the *cost* of failure. The objective is not to prevent failure per se, because that implies lack of innovation and exploration of new ideas. Rather *the focus should be on encouraging risk-taking in exploring new ideas early-on,* but employ disciplined processes, such that:

- The rejection rate of projects are highest in the early stages of ideation when the costs of the project are lower.
- The stages represent milestones at which a new level of investment is needed to move forward.
- The objective is to manage the business risk while testing key assumptions.

[93] Discussion of stage-gate processes draws from the chapter on R&D management methods by John Meyer in Van Atta, Richard, Lippitz, Michael, et al., 2004.



Source: Clareo Partners, LLC

Figure 6. Total Risk is Typically Highest in the Middle Stages of Development

A stage-gate process is a structured framework for managing research and development projects, where the stages represent the phases or steps the project must progress through, and the gates refer to review points or intermediate milestones where the progress and future direction of the project are reviewed against a set of previously defined criteria. Such processes are used by the R&D organizations to: 1) guide decisions on which project to fund, 2) align projects with R&D strategies and organizational objectives, 3) provide guidance on project definition, including scope, desired outputs, integration, and transition of results, and 4) review projects to insure progress, programmatic fit, and priority.[94]

A stage-gate process of this type can be used to plan and manage early-stage S&T projects. Such a process would begin with idea generation and end at the point when the project is either transitioned to another downstream product group for further development or is terminated. The process is intended to discipline the exploration of new component technologies and systems concepts into the organization's overall research, development, test and evaluation (RDT&E) pipeline, and provide the necessary internal and external linkages and integration to determine those that are most likely to succeed.

Some users have raised concerns that a traditional stage-gate process is best suited for managing well-defined product development efforts, and that it does not handle the early "fuzzy front end" of research and development very well. However, this criticism has been successfully addressed by a number of organizations that have modified the process to encourage the necessary flexibility in the early stages and still maintain a structured management approach. One variation of this approach is sometimes referred to as the *technology* stage-gate method, which has been implemented by several firms, including by DuPont as its Apex process. In a technology stage-gate process, rather than a traditional stage-gate mechanism, the gates are driven primarily by technology advancements, which are inherently less predictable than

[94] Griffin, 1997, 429–458.

traditional stage-gate phases. This means that the gates will often be event driven rather than schedule driven, or more likely, driven by both events and schedules.[95]

The stage gate process may look like a uniform set of steps, but in reality it needs to be very flexible. It should be applied according of the needs of the specific project being reviewed and the type of concept being developed. Thus corporate R&D projects, as opposed to usual business unit product developments, often fall into three categories:

1. Platform (or flagship) projects——These are projects that would radically change the way a current broad product category is performed, such as the shift from desktop to laptop personal computers.
2. Leap-ahead projects——These are projects that represent a major advancement in an underlying technology, component, or subsystem for a current product or system type (these projects may or may not come from a radical innovation promotion group; they differ from the first type in that they are somewhat less "radical" in both their degree of change and breadth of scope). An example of this is Intel's tri-gate transistor for ICs.
3. Strategic technology projects——These are projects that represent emerging technologies that have the potential to dramatically change components, subsystems, or systems but where the application has not yet been well defined. IBM's and Applied Materials' exploration of graphene-base integrated circuits is an example of strategic technology development.

Because of the significant differences between these types of projects, the tasks that would be undertaken in each stage could vary considerable. The issues that would be examined during each gate would similarly differ depending on the type of project being reviewed. Thus, the stages and gates for any particular projects should be custom tailored to the needs of the concept.

The stage-gate process should focus on:

1. Refining the concept——Especially in the early phases of the process, refining (or tuning) the concept is not an easy matter. For example, going from the concept of using nanotechnology to a specific, implementable application would require considerable effort to sort out options to ensure the right target is selected.
2. Determining if the concept is actually possible——In the broadest sense, determining whether a concept has any chance of really working is not straightforward. A good example here is the case of inertial guidance technology. Early on, many experts argued it simply was not possible, and this hurdle had to be overcome to proceed with development of the concept.
3. Determining if the concept is practical——As with many concepts, they may be technically feasible but totally impractical. Sometimes, the introduction of a new

[95] Ajamian and Koen, 2001, 267–295.

technology causes other unforeseen difficulties that need to be addressed. Again, inertial guidance is a good example. It took many years to achieve the hundred-fold or more improvements in component technology needed to achieve practical performance goals.

4. Determining if the concept is desirable——An innovation may be possible and practical but still not desirable for a variety of economic, political, and social reasons. Similarly, an innovation may not attract much interest and may languish because it is an unwanted orphan. Management must determine whether the innovation may not be seen as desirable by existing business units, but could offer the prospect of a fundamental new opportunity. The challenge would be to implement a strategy that will convert the orphan into a prize.

5. Positioning the technology for the next stage of development or insertion——The technology stage-gate process feeds into a downstream mechanism for further development. Consequently, the technology stage-gate process must lay the groundwork for this transition in order to make it as smooth as possible. This involves engaging the necessary stakeholders and generating the information required to facilitate the transition. It also implies bringing the technology to a suitable readiness level for transition. In this regard many firms, most notably GE and Boeing, have embraced the Technology Readiness Level (TRL) concept. Here an important point is that the TRLs need to specifically assessed and even more importantly that these assessments are explicitly used in the technology gate decisions. (See section 5 on GE's use of TRLs.)

B. Gatekeepers

Another key aspect of the stage-gate process is the makeup of the gatekeepers. The gatekeepers are a group that is responsible for conducting the gate reviews and deciding whether a project should move to the next stage. This group also approves the tasks to be accomplished during that next phase and the resource levels, subject to the normal budgetary procedures for the project. Because stage-gate processes have become widely used in R&D organizations, several best practices have been developed on how gate keeping should be performed. These gatekeeper rules of engagement include:[96]

1. Gatekeepers must hold the meeting and be there. Postponed or cancelled meetings are not permitted, and those not attending are considered to be voting "yes" for the project.

2. Gatekeepers must have received and read the meeting materials and be prepared for the meeting. No last minute reading is permitted at the meeting. If there are show

[96] Cooper, Edgett, and Kleinschmidt, 2002b.

stoppers, then the meeting facilitator is contacted in advance so that participants are not surprised.

3. Gatekeepers cannot request information beyond that specified in the stage deliverables.
4. Gatekeepers must make their decisions based on the criteria specified for that gate. Each criteria must be addressed, and a conclusion reached by the group. A scorecard will be filled out by each gatekeeper.
5. Decisions must be based on objective facts and criteria and not emotions or hidden agendas. All projects must be treated fairly and consistently, including uniform application of gates.
6. A decision must be made at the meeting, and the project team must be informed immediately and face-to-face.

Sometimes gatekeeper meetings are difficult to complete due to busy schedules of senior personnel, travel pressures for geographically separated members, and conflicting workload priorities. To overcome these problems, some companies have been experimenting with concepts such as virtual gate meetings where only the project team is physically at the meeting place. The gatekeepers receive the preparatory documents in advance and participate electronically (e.g., by video conference). They also submit their scores on-line. The scores are discussed until a consensus is reached and the results are discussed with the project team. Some organizations are also experimenting with self-managed gates, in which the project team also serves as the gatekeepers. However, this in only used for some gates when the risks are relatively low. A variation on this approach is to use gatekeepers that are not part of the normal stage-gate process, thereby providing a type of peer review of the project. Some organizations are also beginning to encourage the project teams to make their own recommendations prior to the gate meeting. In this way, the actual gatekeepers are viewed as more of a secondary review panel, thus avoiding the necessity of boring down to investigate details.

C. Project Evaluation: Best Practices

Several new product development practitioners and others who have assessed the process have identified important attributes or best practices that affect the success of stage-gate processes. These keys to success include:[97]

1. Leadership support

Like most changes within organizations, the implementation of a stage-gate process does best when it is supported by top management. Such support is critical if the process is to become an effective means of generating essential concepts and technologies. As a minimum, top management needs to participate in the kick-off of the process and be visible and supportive in the various review stages. Having a senior manager serve as an executive sponsor and advocate for the process is also desirable. Also, having senior executives acknowledge and reward those individuals responsible for the success of the process is an important aspect of any type of change management.

2. Adequate resources

Having available adequate resources for both implementing the process and supporting the resulting S&T projects is critical to success. Without adequate resources, quality of execution suffers, time delays occur, team morale suffers, and only low impact technologies emerge from the process.

3. An appropriate process design

Although several standard stage-gate processes can be acquired from various consulting organizations, it is important that the process chosen for implementation be tailored specifically to the needs and characteristics of the using organization. Best practices used by other organizations are important, but they first need to be subjected to a critical assessment to be sure than can be properly used in a particular situation. Thus each stage-gate process must be customized to meet the using organization's needs prior to implementation. Areas that are particularly troublesome in process design include structuring the "fuzzy front end," establishing appropriate cross-functional teams, and creating and implementing tough decision gates—that is decision points that actually can terminate projects.

4. Defined roles and responsibilities

Implementing a stage-gate process requires the coordinated efforts of many people, and it is important that these roles and responsibilities be defined in advance to ensure effective implementation. Of particular importance are the gate keepers (i.e., decision makers), the project

[97] There is a growing literature on this topic, which IDA reviewed including: Cooper, Edgett, and Kleinschmidt, 2002a, 21–27; Khurana, and Rosenthal, 1998, 57–74; Pitts and Jones, 2003.

leaders and teams, and the process manager, the individual responsible for defining, championing, and implementing the process.

5. Implementation plan matched to the organizational situation

An implementation strategy needs to be built upon consultation with and involvement of affected stakeholders and initial trials and successes that can lead to successful institutionalization of the process. Thus an effective implementation plan must be both participatory and integrative in order to achieve sustainable results. And because each organization's culture is different, the implementation plan must also be designed with an eye towards lessons learned from other successful implementations that have been achieved by the organization.

6. Effective communication

A significant level of effort is invested in designing an appropriate process, and it is important that the insight gained from this effort be communicated to all the participants in order to increase their knowledge and obtain as much buy-in as possible. Therefore, a communication plan should be part of the implementation strategy.

7. Focus and discipline

Two of the most common problems encountered with new stage-gate processes are undertaking too many projects and the inability to terminate marginal or underperforming projects. There are many underlying reasons for these difficulties, particularly regarding the inability to kill projects. These reasons include pursuit of pet projects or those mandated as "must do" by senior management or external organizations, unwillingness to cancel efforts that represent large sunk costs, and lack of effective gating mechanisms to control what flows through the S&T pipeline.

A number of techniques can be used to focus the process, such as the creation of an explicit S&T innovation strategy to set direction and guide activities, the application of prioritization schemes within stages to determine which projects are within budget limits, and the use of a portfolio management process to ensure balance among competing resource demands. In the end, it is far better to adequately fund a few good projects than to attempt to pursue too many efforts that are underfunded and understaffed, and thus unlikely to succeed.

8. Progress measurement

A few carefully chosen metrics should be selected to measure the progress in implementing the stage-gate process. These metrics should include tracking implementation milestones against target dates, the number of projects in each stage and dwell times, attrition rates and reasons, progress towards meeting overall process goals (e.g., number of projects by stage, funding levels, and number of successes), and the impact of success stories.

5. Transition and Scaling [98]

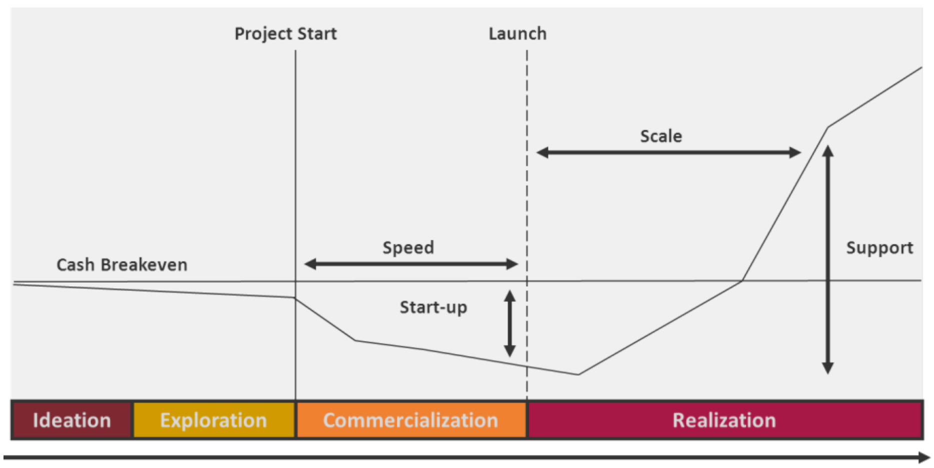
The previous sections described how many companies have made the formerly “fuzzy front end” of R&D more systematic and productive by implementing explicit procedures for generating, collecting, and evaluating new technological capabilities and developing and selecting those few prospects that are judged as providing the best prospects for new products, new production processes for more competitively making products, or even new businesses based on these products and processes. However, despite these sound planning and management efforts, R&D projects often stall at the back end; that is, at the point of scaling technologies and transitioning them into commercial products. In other words, the bottleneck in R&D management today is not so much coming up with ideas or developing new concepts, but rather moving them successfully into the marketplace, scaling their production, and finding an organizational home for the business within the company.

Some of the issues with transition and scaling are fundamental. First and perhaps foremost, intrinsically any new product offering has a set of risks beyond the technical performance and capabilities of the product including the unknowns of the future market, the availability of financing for scaling into production, the firm’s own internal capabilities to absorb and effectively manage the new product’s entry into production and marketing. While the R&D processes discussed above include assessments of these risks, even the best processes cannot eliminate risks. Moreover, firms must balance the risks entailed in bringing out products against the potential impact the product could make. More incremental products using current, perhaps improved production processes may substantially reduce transition risks, but the product may be obsolete relative to a competitor’s more advanced, technically challenging, but riskier product. Therefore determining how much risk to accept when introducing a new product (and attendant production processes) is a crucial decision that the firm must make—essentially it is an informed bet based on judgment, experience, as well as customer-focused competitive assessments. Basically the question comes down to how radical a departure from current, known products and processes, and business experience does the firm want take? The costs and risks of transition and scaling can be reduced substantially, if done very incrementally relative to current practices, but the question the firm confronts is whether such less costly, less risky approaches will lead to products that are accepted in the market and thus provide revenue growth and profits.

Within the firm, successful R&D projects may outgrow their incubators but not demonstrate prospects of sufficient revenues to garner the attention of current business units. In fact, the prospective new product might be perceived as a threat to the core business, at best a

[98] This section builds on the discussion of transition and scaling in Wolcott and Lippitz, 2010.

distraction of firm resources and attention. If the idea is truly new, executives may simply not understand the potential. Moreover, the shift from exploratory development to implementation often entails costly capital investments in production tooling and significant marketing expenses. Why spend millions on a new business that might not produce significant revenues for years when those same dollars could be used to produce more revenues today in known markets? Procurement or quality control organizations might impose their standards on a new concept prematurely, fatally delaying its market entry by requiring it to conform to strict maintainability or other corporate standards. These kinds of problems can arise even when there is no advanced technology involved, but if the technology creates further implementation risks and costs, it adds to the uncertainty of the value proposition.



Source: Clareo Parners, LLC

Figure 7. Typical Cash Curve for a New Business—Scaling Represents a Major Investment

From the review of the literature and the interviews IDA conducted the most prominent lesson we learned regarding transitioning technology is that frontrunner companies assiduously avoid introducing immature products and processes. This point was made explicitly by a number of firms, including Intel, P&G, and GE. While it is intrinsic to the project management processes discussed in Chapter 4 to evaluate whether to go forward into development with a project, underlying the process is a management ethos to minimize making what might be termed preventable errors in inserting insufficiently proven technology by effectively employing and implementing these processes. This is shown most explicitly in the discussions with GE, as elaborated below.

A. Example of Managing Project Transition: General Electric (GE)

A key point specifically emphasized by GE in interviews with IDA was not moving into product development with risky technologies. To avoid this, GE explicitly assesses Technology Readiness Levels (TRLs) in a rigorous tollgate process. A key practice at GE is to *only move into new product development with mature technologies.* GE's experience has made clear that if a firm tries to move to development of a new product with immature technology, the result will be unsuccessful. Thus they “do not do both technology development and product development” in the same project. The most likely way to succeed is to make sure the technology is sufficiently mature and key transfer functions are developed *before* a new product introduction program is started. “If you try to do invention within the program, the project will be unlikely to succeed. Programs cannot start with TRL 2-3 techs… This will cause things to fall out due to uncertainty. New product introduction is complex enough without having to deal with the risks of unproven technologies. When you are at the point of starting up the production plant you cannot be changing things.”[99]

GE’s ethos is to demonstrate sufficient feasibility to know that it can execute the new product development with a very high degree of certainty. If better performance is needed, then a multigenerational product approach must be laid out that segregates the two activities—technology development and product development.[100] Overall rigorous discipline is required on making the determination of technology maturity. Moreover, GE’s experience has been that when this discipline is adhered to, then product development can be much shorter and costs will be substantially lower with a more reliable introduction of the product.

> Within GE this is something that has been learned over and over again. When we have backed off this rule there have been bad experiences. Now we know this works and we’re successful so there is good adherence to separating new product introduction (NPI) and tech development and there is a lot of focus on determining that the technology maturity is right before the technology goes into a product.

GE uses a rigorous tollgate project assessment process. To make this work, it is essential that success criteria be defined clearly upfront. There is an ethos that it is better to kill projects early if they are not likely to succeed. “Within GE we are challenging programs all the time. Even if a project is in the Op Plan, if it is off plan we will stop or redirect it.”

One concern is that over time tollgate processes can become too bureaucratic. They usually start lean, but often more criteria get added, which can bog the process down and make it cumbersome. It takes discipline to keep the process tight and lean and it takes good people to make the process work. A focus on a set of key elements is needed with oversight to keep the process from collapsing under its own weight.

As a *research* organization (as opposed to a development organization), GE Research expects that 80 percent of the research will fail—that is, will not make it into a development program. Research projects will be stopped either because the technology won’t achieve what is needed or it is determined that the market has changed and the technology is either no longer

[99] All quotes in section A. are from IDA interviews with GE executive, August 26, 2011.

[100] See also Intel interview discussion below on its “tick tock” approach to multi-generational product-process development.

needed or cannot meet the new market need. “At GE Research success is not just getting a project done – it’s making the right decision… If a technology development will not achieve the required [specified] results, then ‘success’ is killing it sooner rather than later.”

GE Research focuses on research in the range of TRL 3 to 4—it is generally understood that this entails more uncertainty and higher risk than R&D conducted at the BU level. Thus it is recognized that success is not just getting through the tollgate, it is determining whether a potential technology should get through based agreed upon tests and criteria. This approach relies heavily on two important facets underlying R&D at GE: First, establish clear expectations of success factors upfront during development of GE’s Growth Playbook process, Op Plans and “T Process.” Second, hire the right people and incentivize good decision-making and teamwork.

This approach required complete culture shift within the research organization: “we needed to inculcate that we should celebrate learning” rather than simply getting through the tollgate process. This places an important role on management feedback in the research process, including performance reviews. Thus in the performance review sections on value and performance and as part of goals and objectives this needed to be reinforced. The researcher should be given clear credit for having assessed whether a particular approach either worked or did not. The researcher should be able to state “I did this and this was of value since I learned that it should be killed and then I was able to work on something else.”

The earlier the TRL (2 or 3), the more failure is expected. However, by the time a project gets to TRL 6—failure is a bigger issue, raising the issue: how did we get here? The tollgate process needs to explicitly identify for each phase what needs to be done before moving to next phase—or what risk remediation must be taken. Adherence to the tollgate process must be rigorous to avoid technology creep.

B. Transition and Scaling Practices

In general, drawing on the business literature shows there are several practices that appear to make transition and scaling a surmountable challenge for firms:

1. Engage in complete business system design up front, to help anticipate where the transition and scaling problems are likely to occur. Some firms have formal processes for integrating their basic assumptions about customer value propositions and the competitive ecosystem as they consider different business systems. Successful firms select particular vectors of the business system, based on corporate strategy, and build broad competency in them as a competitive advantage. For P&G, for instance, their Connect+Develop approach leverages their strength and resilience in value capture, channels, presence and brand. The need for considering business systems is particularly important for breakthrough H3 concepts, which often represent entirely new business models that are best commercialized independently from existing BUs. Applied Materials, for example, creates a “minienvironment” under the CTO (but often within a BU’s R&D center). Maintaining regular customer input is critical to insure that there will be a

willingness to pay for the new technology and, more importantly, that customers are committed to making the organizational and process changes that may be required for the new technological approach to realize its full potential.

2. Explicitly address BU disincentives. “Corporate antibodies” (internal resistance to change by existing incumbent business leadership) to new businesses are the bane of innovation projects. Firms that address the problem head-on tend to do better. One of the more effective methods, where possible, is to simply create a new BU to house the new opportunity. Some firms have standard processes for creating and staffing new BUs. Others have formal, corporate-level processes—e.g., control of staffing—that serve to mediate BU interests.

3. Conduct transition planning. In some instances, bypassing existing BUs may not be workable or desirable. In such cases, explicit transition planning, especially for resources, is required. Innovation projects are generally required to obtain investment and oversight from BUs, sometimes at relatively early stages of the process. Researchers often move with the technology to support implementation as part of collaborative teams that include BU managers. Some firms have formal programs for rotating researchers in and out of their laboratories in order to build relationships and understand BU needs, as well as provide incentives in personnel evaluation that favor those who support transition and scaling.

4. Hire and support forward-thinking business builder managers who are skilled at navigating the turbulence of transition and scaling. The right manager for an innovation project is not the same as the right manager for the development of a new product or for an acquisition. Transition and scaling demands flexibility in building the business model, which requires a different type of experience and disposition from either early-stage technology or product exploration or management of an established business.

5. Build competencies in experimentation during the scaling phase. For some firms—especially those whose products are complex or highly integrated—the ability to build and experiment with prototypes efficiently is valuable. Intel builds prototype chips in the Intel Architecture Group to assess new chip functionality, such as the tri-gate transistor structure. They build iterative functioning models of the IC with these structures as proof of principle devices with increasing complexity, and they test these thoroughly to evaluate whether they are ready to be inserted into actual products. Building prototypes also permits early market experimentation and adaptation, which can be invaluable for finding the most compelling customers and business models through which to go to market. The philosophy here needs to be to “fail early and cheaply” rather than spending too much time and money on elegant, corporate-sanctioned experiments that may be designed more for internal political reasons than for expeditiously advancing concrete learning goals for a concept. Thomas Edison’s words should be a guide to expedient experimental design: “I have not failed. I have merely found ten thousand ways that won’t work.” Of course, he meant “ten thousand quick and inexpensive ways.” Modern modeling and simulation technologies support this kind of prototyping.

6. Conclusions: Implications for Department of Defense (DOD)

The focus of this study has been on best practices in commercial industry research and development management. A final consideration is whether and how do the ways in which the top performers in commercial industry have organized and managed their R&D provide insight for the Department of Defense? Before making any observations on this topic, it is important to point out that this study did not examine DOD R&D management. This has been a topic of considerable study both within the Department and by a broad range of organizations outside of DOD including, especially, the Defense Science Board, the National Academies, the U.S. Government Accountability Office (GAO), various Federally Funded Research and Development Centers (FFRDCs) including IDA, RAND, as well as many others. It is also important to note that the focus of these studies and assessments range widely from the management of specific aspects of defense R&D programs, such as the defense laboratories, to overarching assessments of the value and return of DOD's R&D investment to developing and fielding new weapon technologies. In selecting particular industry best practices for DOD consideration, the IDA study team was informed by these studies as well as its own previous work in the area.

A. Fundamental Differences

The organizational context of defense R&D, in contrast to private industry, must be carefully differentiated: DOD conducts R&D within its own governmental institutions, such as the defense labs, but also funds R&D through contracts to a wide range of performers—defense contractors, universities, private firms. This R&D is embedded in a broader system of science, technology development, and acquisition that is budgeted for and managed by the DOD, the White House, and Congress for achieving a diverse set of goals that include the development and acquisition of weapons systems and related technologically based products for use by military. In this regard DOD is the developer and acquirer of systems for its use that it pays others as contractors to provide. Thus, DOD is the *customer* who specifies its needs and formulates these into requirements that become embedded into the R&D and acquisition systems for others to execute.

The scale and scope of the DOD R&D enterprise dwarfs that of any individual private company. DOD's major defense acquisition programs (MDAPs) require very large–scale technology developments integrating numerous complex subsystems into an overall system and even into "systems of systems." Such developments are massively greater in scale and cost than the vast majority of the development programs of commercial industry. At the same time, the DOD acquires these capabilities in relatively small numbers over much longer periods of time than is usually the case for commercial products.

Importantly, commercial industry has much clearer, simpler, and more specific metrics of results than does DOD. Generally commercial firms define results in terms of financial results, particularly profits and revenue growth. Thus, the value of R&D is expressly stated in terms of how it leads to increased revenues while sustaining profits. Many firms recognize that in technology-driven businesses R&D can provide important means to identify, develop, and implement new products and related production processes that provide the basis for growth. Thus, the R&D of the enterprise often is evaluated in terms of how well it is leading to the introduction of new products and how successful these are in the market.

DOD's ability to measure the return on its investments in R&D is much more difficult than a private company because the desired end-goal is the much broader notion of sustaining and maintaining national security. In this context, DOD has struggled to clearly define how it should measure returns from its R&D. One rationale for DOD's R&D is to provide the basis for new products that provide technology superiority. But, this raises such questions as whether technology superiority is itself measurable: How superior across what domains? Where do we want to be just a little bit better—where do we want to be massively superior—for what against whom? Moreover, can DOD be *superior* today in most technologies of relevance relative to the commercial sector—such as microchips, robotics, or distributed computing? How should DOD measure its application capabilities in these technologies areas when they rely heavily on commercial technologies? Thus, for DOD R&D is supported to provide results to it as a customer for the development of capabilities that are aimed at higher level outcomes, which are both more removed from the conduct of the R&D and much less tangible than those of industry.

Moreover, in the area of basic research, DOD serves as a major funder of basic research for the nation. Basic research creates general capabilities in phenomenology, tools, and theory rather than applications. This is in contrast to the trend in commercial industry over the past two decades, which has come to shift basic research to small businesses, universities, and government. Therefore, while the commercial firms IDA examined could assess basic research results solely for their potential to create new products, DOD must also give weight to its responsibility for nurturing the nation's broad scientific base.

B. History of DOD Using Commercial Practices

These differentiating factors make the direct implementation of commercial industry practices challenging (and perhaps in some instances inappropriate). However, there has been a considerable effort, for at least the last twenty-five years, to use commercial industry management practices as a means to improve DOD's management of its technology development and acquisition processes.

The idea that DOD could benefit from adopting commercial best practices gained prominence in 1986 with the report of the Blue Ribbon Commission of Defense Management (known as the Packard Commission, after its leader, David Packard, co-founder of the Hewlett-Packard Company). The Packard Commission report, *A Quest for Excellence*, called for fundamentally altering the organization of defense acquisition to mirror best industrial practices: For example, clear command channels, stability, limited reporting requirements, small staffs with high quality personnel, dialogue with users, and extensive use prototyping and field testing prior to full-scale production.[101] The Goldwater-Nichols Defense Reform Act of 1986 implemented many of these recommendations.

When William J. Perry—a member of the commission—became Secretary of Defense, he spearheaded radical changes in defense acquisition aimed at increasing the use of commercial technologies and capabilities in defense systems. The Federal Acquisition Streamlining Act of 1994 and the Defense Acquisition Reform Act of 1995 paved the way for DOD to make greater use of commercial technology and management practices. These actions, particularly the reversal of DOD policy on the use of military specifications to give preference for commercial solutions, fostered significant changes in DOD acquisition favoring commercial practices. In areas such as information technology, DOD has embraced commercial products and practices, but also develops its own networks in unique ways.

Since then, there have been other commissions and reports but less real action toward adoption of commercial practices. In 2003, the Joint Defense Capabilities Study, chaired by Pete Aldridge, recommended a capabilities-based process for identifying needs, creating choices, developing solutions, and providing capabilities, replacing the Service-driven requirements process. In 2005, The Defense Acquisition Performance Assessment Panel suggested that DOD "fully implement the intent of the Packard Commission" by rebuilding of the acquisition workforce, undertaking more stable budgeting, increasing combatant commanders' role in the requirements process, and undertaking better long-range planning cooperation with industry.[102]

C. Practices for Consideration

These differentiating factors make the direct implementation of commercial industry R&D management practices in the DOD challenging and, in some cases, inappropriate. Still several best practices pointed out in a recent IDA paper are confirmed by this study and some additional practices bear mention.[103] The following commercial industry best practices for R&D management merit assessment in the DOD context:

- Top corporate leadership is actively involved in and maintains close control of setting direction for R&D, monitoring its results, and then making course corrections. The

[101] *A Quest for Excellence*, Report of the Blue Ribbon Commission of Defense Management, 1986.

[102] Kadish et al., 2006.

[103] Van Atta and Bovey, 2011.

active involvement of very senior management is deemed necessary by most of these firms as essential to commercializing technologies successfully.

  - How senior is very senior varied among the companies; it did not necessarily mean the CEO of the corporation, but it always meant at least the head of the strategic business unit and an executive outside the R&D establishment.
  - Senior executive involvement is important to build a culture that encourages intelligent risk taking while also rewarding researchers who are forthcoming about the need to end their projects.

- Corporate, business unit, and innovation strategies are explicitly linked.
  - Corporate and business unit strategies are articulated in terms that guide an integrated approach for technology innovation development.
  - Selection of technology development thrusts to begin and continue is consciously mindful of the corporation's broader strengths and weaknesses.
  - Strategy includes maintaining long-term research in good times and bad when the bias of business units is toward the short-term. An example is the "3 Horizons."
- Best practices include a coordinated and coherent corporate effort to execute open innovation. This involves tapping abilities to scout technologies outside of the company, to work in industry collaborations, etc. It involves efforts to:
  - Attract more outside collaborations with R&D partners (e.g. industry, academia, governments and NGOs)
  - Develop and employ decision support tools for evaluating technology development through partnering with external R&D performers linked to a company's own labs
  - Improve how a company finds and engages new R&D partners
  - Orchestrate corporate-wide collaboration with university R&D performers and government laboratories, as well as large and small R&D businesses
- Among the companies studied, the use of what has come to be called a stage-gate process are successfully employed. This success is related to three features:
  - Stage-gate processes being applied *early* in the flow from idea to product. It was generally applied at the equivalent of transitions between DOD's Applied Research to Advanced Technology Development (BA 2 to BA 3) while the DOD 5000 process picks up at Milestones MDD, A and B.
  - Stage-gate processes generally have serious early involvement of marketing and manufacturing organizations, and sometimes the direct involvement of potential customers.

  - Stage-gate reviews are seen as providing direction to a project, but they usually are empowered to modify or even terminate R&D efforts. An important objective is to kill low potential projects early.

- Generally these companies assign a champion, often self-selected, to a promising project. This person provides strong business guidance to the project team. Also the champion is senior enough to have access throughout the firm and knowledgeable enough of firm culture to help the project avoid pitfalls that could lead to its unwarranted demise, including as a casualty of the risk aversion of some within the stage-gate reviews.

- Identifying potential customer needs is an important effort that goes well beyond simply asking the customers what they want. It involves serious research in itself to ascertain market potential.

- Portfolio management is employed across the spectrum from research through development to transition. It often includes:

  - Quantitative analysis of the revenue and profit potential of projects and comparisons among projects

  - Technology steering groups to oversee several R&D projects that must all come together

- Transition planning is an important issue early in development.

  - Engage in complete business system design up front, to help anticipate where the transition and scaling problems are likely to occur. Address business unit disincentives head-on.

  - Build competencies in experimentation during the scaling phase. *Do not attempt to transition immature technology to manufacturing.*

- Among these companies, there is generally long-term commitment of people to projects.

  - The turnover among stage-gate reviewers is relatively slow and never wholesale.

  - As important, turnover among project participants was low. It was not unusual for researchers who invented the technology to lead it into and through production. Manufacturing and marketing specialists are often assigned to research teams early (e.g., at a point equivalent to the BA 2 to BA 3 transition), and they stay with the project well into its life as a product.

Without having conducted a careful examination of current R&D practices in DOD, it is not possible to say that all of these lessons from the best of class in commercial industry will be usable in DOD. Application within DOD of some of these best practices might well require substantial changes in the organization and management of R&D. Nonetheless it appears that a serious examination of the possibilities will undoubtedly produce some concrete recommendations for improvement.

D. Observations

Industry R&D is increasingly focused on market outcomes. Hence, the findings of this study are most relevant for defense systems in later stages of development, where R&D is controlled by acquisition programs and prime contractors. DOD and its contractors have adopted practices such as stage-gate management, and DOD is just adopting Technology Readiness Levels and considering Manufacturing Readiness Levels. This study did not assess their effectiveness, but this study's findings on project management should certainly be relevant.

In particular, industry has emphasized that to be effective stage-gate decision processes must be treated as more than just a process to go through. At each stage, specific questions and concerns must be raised and seriously considered. Making decisions to change the course of or stop projects or programs early if they are not leading to the desired outcomes is crucial. Many firms noted that making these decisions—and making them stick—is hard and takes strong corporate-level support to achieve. Indeed, some firms noted that implementing an effective stage-gate process requires a new ethos, even a change in corporate culture. In regard to using metrics, such as TRLs, again, the question is not whether a specific metric is used so much as how the data on the metric is obtained and objectively assessed as input into the stage-gate process. Perhaps the clearest way of stating this is that firms who make these management processes work have emphasized substance over form. Underlying the process is the clear intent to make better decisions sooner.[104] They emphasize that getting these results takes considerable effort and investment of time by upper management, but most crucially it requires gaining the commitment of the staffs conducting the reviews to making the necessary decisions objectively and with the best overall interest of the organization in mind. In a firm where the benefit of such sound decisions is reflected in corporate success the employees have a vested interest in overcoming the more parochial interests of individual projects. Can this also be the case in DOD?

Cost, schedule, and performance are the essential trade-offs in any development activity. In today's world, being too late with a needed capability is often worse than not achieving the fully desired level of performance, in the same way that being late to market can be fatal for commercial companies in fast-moving industries.

The spiral development of capabilities in which a limited number of a major system are produced at any given time and are modified iteratively, has been a goal of DOD acquisition

[104] A recent National Academies study, *Evaluation of U.S. Air Force Preacquisition Technology Development,* makes the recommendation, "Technology Readiness Levels must be accurately assessed to prevent programs from entering the engineering and manufacturing development phase with immature technology." (National Research Council, 2011), 97.

reform since the Packard Commission. This approach is fundamental to how much of the commercial industry thinks, but implementing such an approach in DOD systems development demands enforcement of design rules that permit flexibility (at the cost of initial performance) and improved DOD capabilities in rapid prototyping. It also requires capabilities-based metrics and activity based costing to evaluate program value across the portfolio, taking into account a range of systems. Many commercial high technology firms emphasize well-articulated spiral development processes—with Intel's "tick-tock" process perhaps being the prime example for this. The question may be whether this type of process is applicable to defense systems, which are of a much different scale, often stay in the field for decades and for which interoperability is a key factor.

In earlier stages, IDA's experience is that DOD treats S&T as a distributed and decentralized function largely separated organizationally and operationally from product/capabilities development. This distribution of authority and information would make implementation of leading portfolio management practices practically impossible. Unless missions are translated into more generic capabilities, it is impossible to do direct comparisons of alternative S&T and acquisition plans. Tighter coordination would also be essential to implementing commercial best practices around the creation of broad technology platforms.

The concept of portfolio management is deeply embedded in the R&D management of commercial firms—which lay out strategic objectives across the enterprise and develop portfolios with well-articulated processes to determine the structure of the portfolio and to assess it. Importantly, a portfolio is not just a bunch of projects—such as MDAPs—defined by cost or technology area or even a specific type of system. The portfolio is a strategic-set of projects, such as the *innovation portfolio*: which is an approach aimed at delivering "more, higher-quality concepts into the first gate … of the project portfolio process."[105] It "includes the best *set* of concepts that support a coherent strategy, with the awareness that while a few concepts may not provide the same returns as others, the overall aggregation has a high value-creating potential."[106] In such a portfolio, "the concepts themselves are subject to evolutionary pressures within the portfolio, with only those demonstrating positive value momentum and resolution of risk challenges surviving to the next incremental investment phase."[107] Could such portfolio thinking be applied to DOD programs? Perhaps another way of asking the question is whether the current approach to specifying requirements is a deterrent to thinking in terms of portfolios? Moreover, when development programs become so instantiated in the acquisition process can portfolio assessments, with attendant prospects for reshaping the portfolio, be implemented? DOD currently manages many of its early stage R&D projects in "baskets" in each Service but it

[105] Mathews, 2010, 37.

[106] Ibid., 32.

[107] Ibid.

may well be useful to examine the degree to which cross-Service and cross-mission synergy/innovation could be improved by broadening this approach across the Department.

Can DOD use portfolio management approaches, which includes early, objective, and continuous assessment, to avoid this post hoc form of program decision? It should be pointed out that there have been efforts to develop and even implement portfolio-type approaches to Defense systems development and acquisition. [108] While there are organizations and structures and even a Directive[109] that use the terminology of a portfolio concept, the implementation is far from that which would be considered portfolio management and assessment by industry practices.[110] Effective analytic approaches for defining, assessing, and managing such portfolios have not been implemented within DOD.[111]

A leading industry R&D trend is open innovation: Could a system like P&G's "Connect+Develop" work for DOD? In some areas, IDA believes it can. While DOD and its contractors are often limited by the necessity to protect classified information and by export controls, for smaller-scale point solutions, DOD has successfully gone out to commercial industry to respond to urgent warfighter needs in Afghanistan and Iraq.[112] In addition, there have been experiments with venture-style investment in emerging technologies, such as the Defense Venture Catalyst Initiative and the U.S. Army's On Point Technologies group, but these have been limited in scale and scope.

In larger scale systems development, where qualification of suppliers can be daunting, the DOD supply chain is fairly narrow, perhaps by necessity given the specialty nature of many of the subsystems which comprise defense systems. The use of commercial-off-the-shelf (COTS) systems has expanded considerably in DOD systems, raising issues regarding security and availability. Significant reforms in DOD contracting would be required to create opportunities for systems-level trade-offs, allowing systems integrators at various levels to find better or cheaper solutions by looking more broadly for providers. Some small-scale programs aimed at smoothing the path from commercial provider to defense system have been tried but abandoned. DOD could, with effort, learn and adopt commercial best practices for finding and tracking commercial and government investments in advancing militarily-relevant technologies and manufacturing. Boeing's Technology Scouting and Evaluation organization provides an example of such an outward looking organization.

Related to commercial outreach and open innovation is the trend in commercial industry to partner with others in developing new capabilities. One major type of partnership has been

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[108] Porter, Bracken, et al., 2008.

[109] "Capability Portfolio Management," Department of Defense Directive 7045.20, September 25, 2008.

[110] Government Accountability Office, 2007.

[111] Porter, Gordon, and Kneece, 2011.

[112] Van Atta, Lippitz, and Karvonides, 2007.

between industry and universities. In some ways, this may be an area in which industry is learning from the DOD—as DOD has developed strong relationships with universities over many decades. Industry executives in fact emphasized the view that DOD's role in partnerships with their commercial firms has been a crucial element of their ability to take on risky projects. They further expressed concerns that they are finding foreign governments today are at least as supportive of partnering and investing in such "big bets" as is the DOD.

While these observations imply that commercial management approaches to R&D management will be difficult to employ, the alternative is the current approach that has led to results that many consider unsatisfactory—programs that take too long, cost too much, and often fail to deliver needed capabilities.[113] Therefore, DOD should consider:

- Efforts to attract more outside collaborations with R&D partners (e.g. industry, academia, governments and NGOs)
- Developing and employing decision support tools for evaluating technology development through partnering with external R&D performers linked to its own laboratories
- Ways to improve how it finds, evaluates and engages new R&D partners. Can open innovation approaches, such as P&G's "Connect+Develop," provide some pointers on this?
- Undertaking a benchmarking study on best practices for collaborating with university R&D performers and other (i.e., non-DOD / non-defense industry) labs as well as large and small R&D businesses
- Assessing how stage-gate project assessment approaches could be effectively employed early-on and throughout DOD R&D such that programs that are not demonstrating appropriate value are restructured or terminated
- How private industry processes for measuring returns on R&D investment might provide guidance for practical ways to measure the outcomes and value of defense R&D investment
- How to implement and assess a portfolio approach based on strategic objectives across DOD over distinct time horizons
- Developing platform technologies and approaches to transition platform technologies across multiple weapons systems, especially across multiple defense labs, acquisition program offices, and Military Services

[113] Porter et al., 2009.

- Development of its own incubator programs (including technical assistance and early stage commercialization-transition funds) to help it better engage small and medium sized enterprises (SMEs) and non-traditional suppliers (both large and small)

Appendix A
Commercial Industry R&D Overviews

As part of this study, the IDA study team conducted interviews with technology executives at several leading U.S high technology firms that primarily serve commercial markets. These firms are large U.S.-based companies with significant R&D programs that were selected by IDA based on the management literature, their reputation for innovative R&D management and sponsor interest. The interviews were based on a set of questions pertaining to the firm's R&D management practices developed by IDA and reviewed by the sponsor. The interviews focused on the following topics:

1. Business Context and R&D Strategy
   - Corporate vision, market position(s), growth goals
   - Roles of R&D in meeting corporate innovation objectives; relative emphasis on:
     - Supporting near-term product/service development programs
     - Creating an intellectual property (IP) portfolio for future proprietary advantages in core or adjacent markets
     - Keeping abreast of emerging technologies whose application is unclear but that could disrupt markets or foster political, economic or social changes
     - Proactively seeking radical innovations
2. R&D Organization and Resourcing: What has changed in recent years?
   - Executive roles
     - Intensity of top executive involvement (CEO / COO)
     - Role of the CTO, chief scientist or equivalent
     - Roles of marketing, manufacturing and other functional heads
     - Steering and assessment groups, independent advisories, etc.
   - Incentives and accountability at different levels, down to the individual researcher
   - In-house capabilities: People and funding allocation and coordination
     - Overall allocation to R&D
     - Central vs. units [What kind of work goes on where?]

    - Across basic, applied research & development
    - Near-term vs. long-term
    - Use of designated innovation groups to accelerate application or pursue “white spaces”
  - External engagements and networking
    - Out-sourcing to local partners
    - Suppliers, customers
    - Universities
    - IP marketplaces
    - Other open innovation initiatives
  - How recent economic downturn affected R&D. Lessons for down-sizing?
3. R&D Project Management: How have you sought to make innovation more repeatable and predictable as a contributor to meeting growth goals?
  - Sources of concepts for research initiatives
    - Is there a formal process to assess technology maturity?
    - Linking R&D and application possibilities to set research objectives, dimensions, scope
  - Project selection and portfolio management
    - Criteria
    - Analytic tools and measures
    - Use of parallel research (up to competitive prototyping) to reduce risk?
    - Terminating/shelving projects (rate, process, knowledge management)
    - Coping with failure
  - Research team formation, management
  - Communication of research results, to foster application ideas and possible redirection
4. Transitioning and scaling proven new technology offerings into the business (or spin-off)

Before conducting interviews with the R&D executives, IDA reviewed recent business and technology management literature and the companies’ publicly available material on corporate websites and published documents. Often the executives IDA interviewed identified or provided additional publicly available materials for use in the study. The interviews were extensive (often over two hours) and on several occasions the executives were willing to either meet again or conduct a follow up telephone interview to elaborate or clarify points made in the initial interviews. The interviews were conducted on a non-attribution basis (but some executives permitted IDA to reference them). All interview summaries were submitted to the executives for them to review for accuracy and in particular to be sure that they contained nothing that the company was not willing to be allowed for publication in a publicly available final product. From the interviews and published documents, IDA distilled the corporate summaries presented in this appendix.

Applied Materials

Applied Materials (AMAT) is an innovation focused company—this is critical as it 1) focuses on a set of customers with very demanding product innovation cycles; 2) seeks to identify and exploit potential "technology inflexions;" and 3) drives investment in technology leadership to achieve scale to bring down costs and enable differentiation of products while seeking market disruption.

AMAT is a materials processing technology company that focuses on nanoscale manufacturing tools, equipment, and processes for three key markets areas: semiconductor integrated circuits, flat panel displays, and solar photovoltaics. Its first products were equipment to support the semiconductor industry—such as chemical vapor deposition (CVD) equipment. Based on the compatibility of such technologies for flat panel displays, AMAT created equipment especially developed for this as a separate product area. Similarly it developed special equipment and processes for semiconductor-based photovoltaics. Thus, AMAT has an underlying technical expertise base in the materials processes and equipment for processing steps in semiconductor-based product manufacturing. For the integrated circuit industry, AMAT technology has been a key enabler for the continued evolution of Moore's Law. (Applied Materials and similar subtier firms are "the grist for the mill" for Moore's Law.) For solar, a substantial leap in the power potential of silicon-based photovoltaics has been enabled by the innovations in processing equipment and processes leading to the prospect that the current 18 gigawatts of solar worldwide will be 400 gigawatts by 2020 as silicon photovoltaics is projected to reach grid parity in cost to fossil fuel electricity generation.

Applied is embedded in an innovation ecosystem of customers, suppliers, academia, institutions, and venture capitalists (VCs). For example, AMAT will invest in VC deals to enable the development of a supplier, discipline or a nanotechnology application. Within this system, AMAT must be able to recognize and seek ideas from others and collaborate and invest through *strategic investments* to disrupt the current market or enable a new product. New market developments come from both inside and outside. AMAT will incubate internal developments as investment in "inventures." External ideas are identified through relationships with academia, VCs, and merger and acquisition investments. For these external and internal developments AMAT has a structured vetting process—using a score card on such criteria as synergy with strategic business plan, market opportunity, disruption potential, value added in terms of providing a value chain technology for manufacturing, or access to customers.

Examples of external ventures are the acquisition of Italian firm Baccini for solar panel metallization and the acquisition of Precision Wiring, a Swiss firm. Baccini resulted in a thirty times revenue increase in three years, while Precision Wiring resulted in a ten times revenue increase in three years. Critically the CTO and the company's technical organization play a major role in technology due diligence in assessing the prospects of such acquisitions. It is possible to make costly mistakes if they are not properly evaluated according to the vetting process. "[AMAT]…must understand what the capabilities and potential are, what is different in what the acquisition would provide"[1] and especially how it would affect AMAT in terms of timing and capabilities. Their guiding principle is how would the potential acquisition enable the market and the customer? "Acquisition is the quickest pathway to solve customer problems."[2]

AMAT internal R&D is ~$1 billion/year—relative to revenue changes R&D is more constant: Importantly, *AMAT tends to spend more in downtimes.*

Internal R&D—AMAT uses a horizon model (H1, H2, H3) to classify products and markets. (This concept draws explicitly on Geoffrey Moore (2007) "Focus on the Middle Term," *Harvard Business Review*, July–August, 84–90, which drew upon earlier McKinsey work).

> H1 is driven primarily by the business units and is mostly roadmap focused and is customer and collaboration driven. SEMATECH, ITRS and other consortia are important in this process. The roadmap identifies key challenges through a "stoplight" chart. This is development that is highly customer focused in the N+1 and N+2 timeframes.
>
> H2 is primarily corporate research aimed at building on developments identified in H3 that support identified customer needs or present tangible prospects of new products or new market entry. AMAT uses a combination of Process Portfolio Analysis and Product Lifecycle Analyses (gated investment discipline for product development) for determining H2 R&D priorities. AMAT seeks to have 25% of its revenue to result from H2 R&D within 5 years – thus $2.5B of $10B revenues are derived from H2 R&D.
>
> H3 is exploratory R&D aimed at:
>
> – Disruptions in the core market
>
> – Adjacent markets
>
> – New markets
>
> – Foundation technologies
>
> H3 R&D comprises about 15–20 percent of AMAT R&D.

An example of AMAT H3 research is the prospect of graphene-based semiconductor devices. For AMAT, the question is whether robust, replicable processes can be identified for depositing graphene can be developed that can be cost competitive with projected alternative technologies. From AMAT's perspective, this new approach will require equipment to succeed, but there must be some relatively well-defined pathway identified to go from an invention into an innovation. AMAT sees the exploration of the prospects of carbon electronics as primarily the job of academic research. To this end, it is both following developments n this area and also

[1] IDA interview with Applied Materials executive, July 7, 2011.

[2] Ibid.

funding some academic research itself, for example through MIT's Graphene Center, as part of AMAT's investment of $10 million per year funding of university research.

Semiconductor industry is unique in its rapid self-obsolescence. Hence, integrated circuit (IC) equipment suppliers are driven by time-to-product under cost constraints (this includes both product cost and the cost of operations and ownership of the product). The IC industry has pursued the Moore's Law dynamic of continuous reduction of cost per function through reduction in feature size. This dynamic of self-obsolescence through technologies achieving greater density through miniaturization at the nanoscale is the major forcing function for AMAT. Moreover, IC production is the most interdisciplinary field in terms of the breadth and kinds of knowledge it requires. This drives the need to collaborate both horizontally and vertically. The semiconductor industry is a prime example of collaborative innovation. This was driven in the 1970s–80s by the U.S. losing its competitive position in IC production processes.

In contrast the solar photovoltaic and the flat panel display (FPD) industries (as well as the micro-electrical-mechanical systems—MEMS—industry) are driven by a different dynamic—cost per area. Even so with the advances in production tools and processes the FPD productivity has increased twenty times over the past fifteen years.

Major AMAT R&D Centers—twenty worldwide

U.S.: Santa Clara and Austin

Europe: Italy [solar through Baccini acquisition]; Switzerland [Precision Wire acquisition]; Germany

Asia: Singapore; Taiwan [Tainan display]; India [broad focused design R&D for all businesses]; China [two facilities—one solar the other ICs (silicon)]

R&D centers are managed as part of the corporate technology strategy with each organization's focus based on ongoing assessment of its capabilities and talent relative to projected needs and resources. Thus, with acquisitions, for example, a key question is how to rationalize and integrate the acquired firm's R&D with that being done elsewhere in AMAT.

Key Focus of Corporate Technology (CT)

CT's focus is beyond the business units' current [H1] R&D on potentially disruptive technology. However, this is often done with and through the business units in a "minienvironment." The R&D for this more advanced [beyond roadmap] or disruptive capabilities is funded [mostly] by the CTO but often conducted within the BU in its R&D center. This is seen as a means for overcoming problems of technology transfer that would likely occur if the development was done in CT. So, CT assesses when to incubate a disruptive concept inside a BU and use the BU's infrastructure.

Boeing

Background and Overview of Boeing R&D

The Boeing Company was founded in 1916. Through a series of mergers and acquisitions,[3] Boeing today is the world's largest and most diversified aerospace company, with customers in one hundred and fifty countries and 2010 revenues of $64.3 billion. Business areas include commercial jetliners, defense systems, satellite and launch vehicles, systems integration and networking, and advanced technology development, which Boeing pursues with more than twenty-two thousand suppliers and partners around the world. The company employs 165,000 people in seventy countries.

Boeing's total R&D spending has been in the $3.7–$4.1 billion range since 2008.[4] As with many companies, Boeing employs a horizons of growth framework with H1 being near-term—one–three years, H2 midterm—three–seven years and H3 being seven plus years next generation technology. For the near-term implementation (Horizon 1), business units identify what capabilities they need in their products to remain competitive in the near term and then receive a percentage of company revenues to develop these new or derivative products. Business units take the lead and Boeing Research & Technology (BR&T), the company's central R&D unit, provides support. Exploratory research (Horizon 3) is focused on creating and implementing tomorrow's technologies in next-generation products. In all cases, Boeing is disciplined in having engineering teams coordinate with end users, to make sure that customer value is being delivered. The level and type of scrutiny varies with the size and scale of the program. But it is a recurring theme across Boeing R&D organizations, as will be explained below.

Anytime a new product offering like the 787 Dreamliner happens, it means placing a big bet. The greatest opportunity for success and risk is during the product's creation. Boeing also made a major corporate change with the 787 Dreamliner in having critical work done on major subsystems done by suppliers. This shift in risk and responsibilities drove new paradigms for technology development and partnering with suppliers. The focus on international partnerships is driven by the key role of international customers. Work with international partners is expected to grow as it helps to differentiate Boeing and provide more options for the business units. [5]

R&D is performed across Boeing's businesses. Corporate R&D is managed under the Engineering, Operations and Technology (EO&T) function, led by Senior Vice President and Chief Technology Officer John Tracy. EO&T was formed in 2006 to establish technical and

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[3] North American Aviation, McDonnell Douglas, Rockwell International (space and defense business), Hughes Space & Communications and Jeppesen, among others.

[4] Does not include a $2.7 billion reclassification of cost for the first three 787 flight test airplanes from program inventory to R&D expense in 2009.

[5] *Boeing Frontiers*, July 2005, http://www.boeing.com/news/frontiers/archive/2005/july/cover.html.

functional excellence and common systems and processes for the enterprise. Reporting to Tracy are the Engineering, Operations, and Supplier Management functions, and the Information Technology, Enterprise Technology Strategy, Research & Technology, Test & Evaluation, Intellectual Property Management, and Environment, Health and Safety organizations. EO&T employs over 19,000 people.[6]

In recent years, EO&T has:

- Formed in 2006 an integrated Enterprise Engineering function chartered to identify best processes, systems, tools, and training, and deploy them as standards across Boeing. Among other things, this change made it easier for engineers to cross business lines and work on programs across the company.[7]
- Created the Enterprise Technology Steering Team, which supports the Enterprise Technology Strategy function, in 2007 to identify and fund cross-cutting technology needs across BUs, to encourage collaboration across businesses, and to avoid duplication of efforts. The Enterprise Technology Steering Team includes representatives from Boeing Commercial Airplanes, Boeing Defense, Space & Security, Boeing Research & Technology, Boeing Business Development and Strategy, and the Development Process Excellence Initiative team.
- Established nine Senior Technical Fellows within Boeing in 2010—who are elite scientific and engineering contributors; four from commercial, five from defense promoted to VP, Engineering and reporting into the corporate BR&T organization rather than to their BUs.[8] Their charge is to drive engineering excellence throughout program development.
- Engaged in more international technology partnerships. In 2011, BR&T had more than 300 active international research and technology partners, and this number is expected to grow in the years ahead.

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6 Boeing Employment Numbers, http://www.boeing.com/aboutus/employment/employment_table.html.

7 Ibid. The BR&T organization doubled to its present size in January 2010, when nearly 1,000 materials and process technology employees assigned to Commercial Airplanes joined, along with about 1,000 materials, processes and physics and manufacturing, research and development employees from Defense, Space & Security. In addition, experts in product standards from Shared Services Group also became part of BR&T at the time. The move has saved Boeing millions of dollars through the implementation of common research-and-technology processes and the elimination of redundancy.

8 The newly appointed leaders and their technical areas of responsibility are, from Boeing Commercial Airplanes: Mike Delaney, Airplane Performance & Product Architecture; Keith Leverkuhn, Propulsion Systems; Jim Ogonowski, Airplane Structures; and Mike Sinnett, Airplane Systems. From Integrated Defense Systems: Bill Carrier, Structures; Laurette Lahey, Flight & Controls; Jack Murphy, Systems Engineering; Darrell Uchima, Mission Systems Payloads & Sensors; and James Farricker, Networks & Communications.

How are the Horizons Used to Manage R&D?

Technology development horizons are viewed in the same way as an individual's investment portfolio—just as individual investors hold a certain amount of cash for near-term expenses, and stocks and bonds for mid-term to longer-term investment goals, Boeing R&D is conducted in support of current products (products that will be delivered to customers within one to three years), development of products that can be transitioned into the business units over the mid-term (three to five years), and development of longer-term enabling technologies that might lead to game-changing future business opportunities. The levels of near-term, mid-term and longer-term projects are adjusted from year to year depending on business and environmental factors. In making adjustments to the portfolio of projects in the different horizons, consideration is made for maintaining core competencies and competitive advantages, tracking emerging disruptive technologies, and leveraging work conducted by others.

In assessing projects for graduation from one horizon to another, Boeing uses the National Aeronautics and Space Administration's (NASA) Technology Readiness Levels (TRLs) to assess the maturity of evolving technologies. There is a formal gated process, with go and no-go milestones, from conceptualization through incorporation to a system or subsystem.

Project Management

Within BR&T, the Director, Dr. Matthew Ganz, and the BR&T leadership team, makes the determination of whether a project will go forward. Within the major Boeing business units, the decision rests with the technology and program leaders in the business units.

BR&T conducts what is known as a PAD process for BR&T research projects, which involves a yearly assessment of every project. A Program Authorization Document, or PAD, is produced by the technical leaders of every project, and the PADs are presented to Dr. Ganz, the BR&T leadership team, as well as representatives from the business units. While these reviews are conducted in public, Dr. Ganz provides feedback in private to the project leaders as to whether they fall into one of three categories: green (most promising and productive), yellow (promising, but with some issues) and red (questionable or very limited value). Projects determined to be red are first to be considered for elimination, with funding then diverted to green projects and technology areas.

Enterprise Technology Strategy

The Enterprise Technology Strategy organization, reporting to CTO and Senior Vice President (SVP) John Tracy, is responsible for developing a companywide strategy for determining critical technologies. Allen Adler is the current VP of Enterprise Technology Strategy (ETS). ETS has "eight company-wide technology domain teams focused on next generation products and systems. These teams work to ensure the company's commercial, military and space businesses have the necessary technologies to compete and, when appropriate, ensure new technologies are replicated and leveraged across the company to improve quality and reduce costs. The VP for ETS is also executive sponsor of the Technical Fellowship Program, which promotes technical excellence and innovation, and offers a technical career path to the company's top scientists and engineers and oversees the company's involvement with more than 200 external technical affiliations."[9]

Boeing Research & Technology (BR&T)

BR&T, which also reports to Tracy, is the central research and development unit of The Boeing Company. BR&T has nearly 4,000 employees who support "Boeing's existing programs and products, as well as breakthrough technologies for the creation of new products and business opportunities."[10] (The original Phantom Works still exists as an advanced systems organization for the defense market.) Most of BR&T personnel work in St. Louis, Seattle, and southern CA, but there are also research centers in Australia, China, India, Russia, and Spain.

As stated by Dr. Ganz, BR&T focuses on creating business value. "If a cool new technology doesn't provide a benefit to a customer and generate enough money to cover its development costs and make a profit, it isn't innovation, it's art," said Ganz, who attributes the definition to Apple CEO Steve Jobs and other successful innovators. "True innovation happens when invention and business insight intersect."[11] Additionally, BR&T undertakes earlier stage research and university partnerships in areas identified as important for market leadership.

Relationship in Functions and Responsibilities between the CTO, the Enterprise Technology Strategy Function, and BR&T

Under CTO John Tracy, Boeing's Engineering, Operations & Technology organization is focused very heavily on delivering technical services and integrated technical strategies, as well as improving discipline in the technical functions. It has the overarching mission for Boeing to improve growth and productivity by providing the technical and functional capabilities Boeing needs to operate more efficiently and effectively as one company.

Under Vice President Allen Adler, the Enterprise Technology Strategy organization is designed to create a sustainable technical competitive advantage that increases Boeing's growth and productivity. The objectives of the ETS organization are to ensure that Boeing technology plan supports Boeing's business strategies; identify opportunities to optimize the company's investments at the enterprise level using efficient, effective processes; and provide an opportunity to create a one-company culture in sharing perspectives across the enterprise.

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[9] Boeing Executive Biographies, Allen Adler, http://boeing.net/companyoffices/aboutus/execprofiles/adler.html (downloaded August 2011).

[10] Boeing Executive Biographies, Matthew Ganz, http://boeing.com/companyoffices/aboutus/execprofiles/ganz.html.

[11] *Boeing Frontiers*, May 2011, 34.

Under Vice President and General Manager Dr. Matthew Ganz, Boeing Research & Technology, the advanced, central research and development organization for Boeing, provides innovative technologies that enable the development of future aerospace solutions while improving the cycle time, cost, quality and performance of current aerospace products and services. To ensure these enabling technologies are ready when needed, BR&T not only conducts its own development but also works with top government, private and university research centers around the world to quickly find the most innovative and affordable solutions possible. A common challenge for all customers is to find better, faster, and more affordable ways to design, develop, produce, deliver, operate and maintain both current and future products, systems and services. To meet these needs, BR&T technologists typically work in small teams across Boeing and with its technology partners around the world on providing a broad array of innovative solutions.

As the leader of BR&T, Dr. Ganz works as a strategic advisor for all Boeing research efforts. The Boeing business units (Commercial Airplanes, and Defense, Space & Security) have authority for project and program management in their respective areas. Boeing Research & Technology has responsibility and authority for the research within its portfolio.

Boeing Technology Scouting Group

The Boeing Technology Scouting & Evaluation (Boeing TS&E) was founded in 1997, with support from a strong executive champion, and today consists of about ten people within BR&T. TS&E performs a type of open innovation, playing a matchmaking role across the enterprise between external technology sources and internal business needs. TS&E works with the BUs to understand their business environment and needs and to identify gaps in their capabilities for which technology scouts can seek outside solutions. They spend about half their time understanding what BUs need and the other half finding and vetting external technologies (referrals). TS&E is one of several technology scouting teams within Boeing, but it is the only one that uses an external network of referral agents who are investors—including investment arms of large corporations, economic development organizations, venture capital firms, and university technology transfer offices—to find new and indirect value for the enterprise, usually in adjacent industries such as construction or oil and gas. As such, it complements other Boeing networking and scouting efforts by that tend to focus on traditional aerospace or defense suppliers.

TS&E receives hundreds of referrals per year, of which usually over one hundred are evaluated further, and a few transition into use in an application that creates significant value. Usually basis for value is the identification and use of a capability that provides a new solution quickly and for lower cost than if Boeing developed it in house. TS&E teams with colleagues in the business units as well as E&OT do the technology due diligence for a prospective new technology solution. The value of a transition is determined by the business units. Typically

TS&E hosts the evaluation of a technology until it is appropriate for BR&T or a BU to lead. This happens on a variety of timelines depending on the particular capabilities in question.

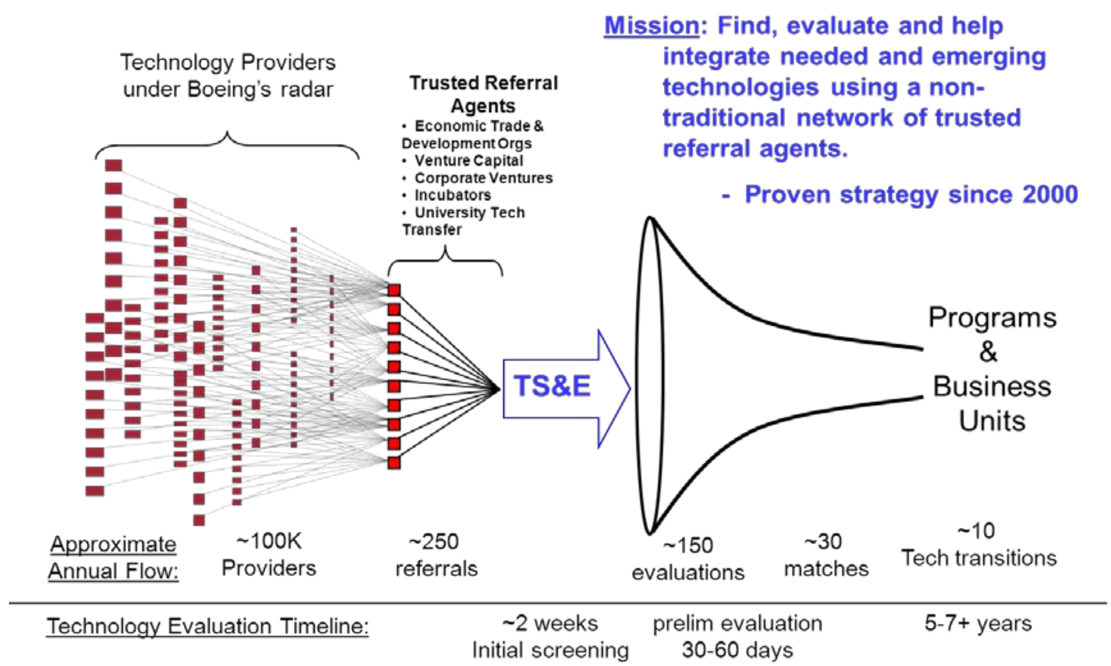

Figure A-1. Boeing Technology Scouting Group External Sourcing and Transition

The success of a partnership depends in part on how well its readiness level aligns with the delivery date of new systems into which the technology is intended to be integrated. Timeframes for successful insertion depend on the particular customer—with considerable variation among active commercial and defense programs. TS&E had its first transition in 2000, and in subsequent years had consistent success with high value transitions that was substantial enough to demonstrate the value to BUs of this outreach mechanism. For example, the group discovered Insitu's unmanned aerial vehicle (UAV) capabilities (ScanEagle) in 2002, and the resulting partnership culminated with Boeing acquiring the company in 2008.

The benefits for technology referral agents who interact with TS&E include a clear understanding of Boeing's technology needs, business units, products, processes and markets; the opportunity to participate in the early stages of Boeing's technology decision loop for acquiring technology; and evaluation or testing of their investments in products and services for aerospace applications. Partners may also receive technical advice on product maturation and integration. TS&E typically seeks external technology providers that are at least at prototype stage, with a TRL level of 4–7 as the most advantageous. For systems with long development lead times, such as satellites, longer-term research may be undertaken. The goal is to identify an insertion point into a system, so if the system is long-term, much of the technology program may be also.

TS&E has learned many lessons over the past decade on what it takes to succeed at this form of innovation:

- At least one internal BU champion is needed to facilitate adoption of a new technology, and these people are essential to success. The champion or champions may be engineers as well as executives, as long as they have a decision-making role for the program that will be receiving a technology or system. A key focus of the team's time is on accessing and continuous engagement with programs or projects to find the potential champions who are a good fit for the capabilities offered.
- Money-for-information is not sufficient to ensure the success of a scouting network. Technology scouting relies on formal and informal information sources, including the personal networks of the scouts. TS&E scouts tend to be lateral thinkers, knowledgeable in science and technology, respected inside the company, cross-disciplinary orientated, and imaginative.
- TS&E seeks to select its customers wisely, with a bias toward devoting its resources to problems where the value and opportunity for use is the most compelling and hence the program most engaged. The group employs a concept of *innovation fit* as part of its assessment process:
  - Is there a clear advantage in adopting the new technology?
  - Can the potential user understand it sufficiently to be comfortable using it?
  - Is the technology compatible with the broader system and the user's activities?
  - Is there an affordable way to test the technology before committing to it?
  - Are there representative places where the user can see the technology in action?
- TS&E works closely with the customers to help them reformulate their issues into generic level problems so as to broaden the possible solutions spectrum. "Needs" that are summarized or specified in databases, forms, or presentations typically do not provide enough clarity on the underlying issues or leave not much room for creativity and innovation.
- TS&E creates a central repository of all "wants" from each BU to support tech scouts in their jobs.
- TS&E seeks to mitigate the risk of openness on company needs using anonymity, abstraction of the problem, and breaking up problems into easily implementable questions.

- TS&E facilitates the screening process of potential solutions by creating a solution submittal form that covers technology readiness, IP aspects, etc.
- TS&E puts extra focus on the transition from incubation to scaling stage (R&D to BU transfer): 99 percent of failures in large corporate happen at that stage. Main reasons for failure are:
  - Lack of ownership at the receiving end
  - Not enough buy-in from the hosting BU
  - Information transfer is incomplete
- In order to effect a transaction, productive engagement with corporate resources such as supplier management, export controls, contracting, and legal departments is critical.

The fundamental elements that must exist in order for a team like this to succeed are: 1) An executive champion or equivalent to make sure the team is well positioned with customers and access to tech opportunities. 2) Team members who know how to pick the few winning high value capability matches and have the skills to bridge the gaps in the innovation process during the multi-year effort to implementation. 3) Large flexibility and diversity of customers and offerings. First person to market wins, no prize for second place. Diversity and flexibility of applications and options for alternates to bridge the innovation gaps can make the critical difference.

Exxon Mobil

Exxon Mobil Corporation conducts research related to their upstream, downstream, and chemical operations. Upstream research is focused on geosciences, engineering, and computing projects supporting exploring for, developing, and producing hydrocarbons. Geoscience research focuses on addressing applied geological and geophysical challenges—such as imaging the subsurface in complex environments. In part, this research supports identification of the best global exploration opportunities and decisions on where to locate exploratory drill wells. Engineering research can include advanced drilling techniques, simulation of hydrocarbon reservoir fluid flow, and development of offshore facilities for harsh environments. The expectation is that the investment in these and other research areas will continually improve the safety, integrity, and efficiency of worldwide activities.

To support the dissemination and implementation of new technology, Exxon Mobil rotates geoscientists and engineers in and out of research facilities. This provides a closer tie between critical business needs and challenges and ongoing research projects. Also, researchers are frequently called upon to address problems in the field where special expertise is needed, which also gives the researchers direct practical experience.

Exxon Mobil conducts collaborative projects co-locating researchers from the lab with a project team from the business unit. Exxon Mobil sees this as an effective technology transfer mechanism. Another technology transfer practice is to move people with the technology. For example, a researcher might be deployed to a business unit with a newly developed technology.

Exxon Mobil sponsors third party research with suppliers or contractors, working in collaboration in some cases. For example, Exxon Mobil might contract for the open development of a geophysical or geological computer application, while developing proprietary in-house plug-in algorithms. The trade off is that in-house proprietary developments bring with them infrastructure requirements, such as training and support, which must be considered.

Rapid advances in computing capabilities have created new research opportunities in the energy industry. New *petaflop* machines are enabling for the first time more complete evaluation of massive geophysical (e.g., seismic) datasets. To fully realize this potential requires research to develop code that is as efficient as possible. Greater processing horsepower, combined with efficient algorithms and computing techniques, has resulted in analyses that just a few years ago required weeks or months to process, now being processed overnight. These opportunities and challenges may be similar to those that DOD faces with massive data streams.

Research Needs

Research priorities are driven by technical challenges and needs of the business. Advisory committees provide inputs on business problems and technical issues and researchers propose ways of addressing these needs. Research advisory committees regularly review research plans and progress to ensure appropriate alignment.

Each committee includes managers from the research organization and from business units (customers) and key senior technical staff, appropriate to specific research areas or themes. The committee members solicit input from operating business units and identify technical challenges and needs. These challenges and needs are then evaluated and generally fall into one of the following categories:

- We are already doing research on this.
- There are external tools or capabilities available to address it.
- We already have the capability but the group providing the input was unaware.
- We are aware of the need and it's been prioritized out.
- For only handful: It is not already being addressed and we don't have this capability—we need to do research on this.

The process has value in ensuring the current research program is on track, identifying key gaps in technology needs, and in identifying capabilities that are already available that some are not aware of.

A senior level cross-functional team, with representatives from business, research and computing, meets regularly to ensure alignment for all geoscience technology development and application across the company. This team addresses issues such as what work should be elevated to a higher priority or what projects require coordination among groups. Importantly, the team members are at the level that they can allocate resources to the priorities and concerns that they identify.

Other Considerations

Understanding when to end a project is as important as knowing when to start it. Exxon Mobil uses a strong stage-gate process for its research projects for staying aligned and on track with clearly defined milestones upfront. This is a focused review process with the end customers in business groups involved in the review. Upfront there is comprehensive discussion of what is needed and what can be done that is explicitly agreed to. The milestones are defined with clear go–no go decisions or explicit course changes as defined in the review.

- Identifying in advance what specific challenges would have to be overcome to successfully develop a new technology is a key part of the research process.
- Whether to apply a given technology is based on its potential to influence a business decision rather than just provide more data.
- For R&D management, there is a balance question between strictly following a research plan and giving the researchers "room to play."

- A key measure for technology development success is "What difference did you make in terms of value to the business?" In this regard, technology deployment and transfer are as key as technology development.

Technology Management

One organization within Exxon Mobil that appears to be of particular interest relative to Defense R&D is a technical organization that serves the upstream. This group has the responsibility to ensure the appropriate technologies (primarily geosciences) are available, supported and applied in operations around the world. This group includes technical specialists who go to sites to support the implementation of new capabilities both developed from internal research and from outside sources. This ensures consistent practices and application of technologies as opposed to isolated individuals trying to implement them. This team manages a consistent, standardized suite of technologies ensuring that the full range of technical capabilities and practices are available to all geoscientists around the world, in all phases of the upstream business.

The technical organization is also responsible for the development and deployment of all geoscientists worldwide and across the upstream function.

Field Testing a New Technology

Field testing major new technologies can be challenging and expensive—e.g., testing a new geophysical tool under operational conditions might run as high $50–$100 million. Funding for this scale of fieldwork is generally not available from research or technical organizations, and is therefore often sponsored by operating business units. This carries the challenge of demonstrating the value of the new technology to the funding project, with the recognition of the inherent risk associated with unproven technologies. Successful approaches to this issue have included identifying a project facing a technical challenge that could only be addressed with the new technology, tool or process; seeking corporate-level *general interest* funding; and funding from a company-level sponsor of the technology in the general interest. In any of these instances, new technologies that require field testing generally have a technical champion (typically a senior technical expert) who can raise the opportunity to senior level management for consideration.

General Electric (GE) Global Research

GE performs centralized R&D at the company's Global Research Center (GRC) and decentralized R&D at the business unit (BU) level. GRC is responsible for ~$600 million in annual R&D, which is ~5 percent of total GE R&D. GRC is headquartered in Niskayuna, New York with other GRC labs located in China, India, Brazil, and Germany. GE is a highly diversified company with a wide breadth of BUs (e.g., aircraft engines, healthcare, transportation, and energy). GRC is unusual in that it does research across a vast array of technologies, such as aviation materials and electronics for medical applications.

Most of GE BUs have their own R&D capabilities, such as the aviation business. For some research, the BUs will conduct its own R&D and will be "primes" with GE GRC as a "subcontractor." In other instances, GRC will be directly contracted to perform specific research for a BU. While the research is usually for a specific BU, other BUs can tap in to GRC developments. The R&D capabilities within BUs vary considerably. Some BUs have extensive R&D capabilities (e.g., aircraft engines) but other BUs have more limited R&D capabilities and rely more on GRC for their R&D. GE does have some government R&D funding, which is generally not pursued primarily on a financial basis, but rather on a collaboration basis for conducting higher-risk, longer-term research.

GE Global Research's primary focus is TRL 3 to 4—but it is involved in all phases of research, even working with BUs in late stage development —whereas BUs generally conduct R&D at TRLs 5 to 9. The main difference is that Global Research researchers generally are very deep in specific technology areas compared to the BU staff, so when special expertise is needed, Global Research can provide it. GE generally relies on universities to conduct R&D below TRL 2.

A key change in GE research today, compared to ten years ago, is that there is much more partnering and collaboration within GE and especially with others outside, including suppliers, customers, universities, and other external R&D performers. The focus now is to determine who is most qualified in the world to succeed in a particular research endeavor and bring together the best team for doing it using internal and external researchers.

GE works with universities for a number of reasons and in a variety of ways. Collaborations with universities provide GE with insights into more basic level research and what's coming down the road. Universities also provide GE with access to some of the world's best talent (including professors and students) for building R&D teams. GE also contracts with universities for R&D (both directed and less directed) as well as to make use of university testing capabilities. GE works with universities through various mechanisms including Cooperative Research and Development Agreement (CRADA)-like agreements, R&D grants, subcontracting and supporting post doctoral research. GE commented that universities are generally not good at commercialization and working with universities can be very difficult. Universities can be overprotective of intellectual property (IP) rights and developing agreements with universities can be very time intensive and costly. Thus, GE is trying to standardize its processes for working with universities across the company to instill more cohesion and focus. It was noted that universities' ability to commercialize technology is generally limited to working with small startups or licensing technology to established firms. GE believes that its considerable scale, combined with diverse BUs, provides unique commercialization opportunities for university partnerships.

Funding

1. Fifty percent of GE Global Research's funding is from the BUs, which is for internal *contract* research. This R&D is generally shorter term and focused on technologies that line up with the BUs multi-generation product and technology plans. This is generally TRL 5–6 R&D. The BUs know how this research will go into their products.
2. Thirty percent of the funds are assessed as a corporate funded tax on the BUs to support longer term prospects and to overcome short term R&D focus of the BUs. This is generally more risky research, but with higher pay off potential (applied research, mostly TRL 4+). This research is managed by the Senior VP for Technology.
3. External funds—(about 20 percent) from business partnerships and government funding. GE sees this as a lever for other R&D.

R&D Portfolio: How does GE Global Research decide what to work on?

Spring is when Strategic Plans and GE's Growth Playbook is developed, which helps determine technology needs for multi-generational technology plans. (In the fall, the focus is more tactical and focused on technology roadmap needs.) The spring meeting focuses on industry trends, longer-term opportunities, identifying customer needs, and ultimately determining where the BUs want to go and their product roadmaps. The next focus is identifying what technologies are needed to develop these products. This is the beginning of multi-generational technology planning, for which the timeframe varies based on business cycle for the different businesses. For aviation, the product window may be ten years out with materials or engine developments being decade-long programs. For shorter cycle businesses, such as transportation, lighting, or appliances, the product turn-around may be as short as six months or one year and the overall R&D window would be three years out.

Once the product roadmap and technology needs are identified, GE establishes direction on addressing technology needs and sets a strategy. The next question is where to do the research: in the business unit; in Global Research; through a partnership? GE has established a specific process for addressing this—"Session T," which brings together the commercial team's executive leadership, the product manufacturing and technology development teams from the business units, with Global Research researchers from technology areas, and even customers. This is an idea exchange and *structured brainstorming* on customer needs and the market and technology options including what is being worked on in Global Research that may be applicable to the needs. This process then addresses what R&D is worth pursuing and how it is aligned with business needs. The output is then presented to the Executive Council for review which then sets high-level challenges for business performance metrics. With the identification of the technologies needed, the next question is how are they going to be accomplished? Will it be done primarily by the BU research unit, inside GE Research, with external partners? This then feeds the fall planning process that sets the company's technology strategy.

Note: CEO Jeffrey Immelt is very engaged in the technology development process and firmly believes that success in the market is based on innovating and having the best products. Half of GE's products have turned over during the last five years. Immelt has been a strong supporter of R&D and sought to increase R&D as a percentage of sales from 3 percent to 6 percent. (It was noted that measuring R&D as a percent of sales is understated by factoring in sales from non-industrial BUs (e.g., GE Capital)). See excerpts from literature below on Immelt's approach.

In the fall, the focus is on developing the Operations Plan to implement the strategy. This lays out the R&D program for the next year and how it will be measured—how progress will be assessed. The Op Plan will pose key questions and "key jugular experiments"—*what tests will be run that will demonstrate whether an approach will work or not?* The objective is to knock risk out as early as possible.

Technology Maturity

A key practice at GE is to only move into new product development with mature technologies. GE's experience has made clear that moving to a New Product Introduction (NPI) with a New Technology Introduction (NTI) (i.e., immature technology) results in projects more likely to fail. Thus GE does not do NPI and NTI concurrently. The most likely way to succeed is to make sure the technology is sufficiently mature and key transfer functions are developed *before* a NPI program is started. According to GE, concurrent product and technology development is a recipe for disaster: "Programs cannot start with TRL 2–3 techs… This will cause things to fall out due to uncertainty…. New product introduction is complex enough without having to deal with the risks of unproven technologies. When you are at the point of starting up the production plant you cannot be changing things."[12] GE's ethos is to demonstrate sufficient feasibility to know that the technology will work and can be made with a high degree of certainty. If better performance is needed that requires using an insufficiently proven technology, then a multi-generational product approach must be laid out that segregates the NPI and NTI activities—technology development and product development. Rigorous discipline needs to be maintained on making this determination of technology maturity. Moreover, GE's experience has been that when this discipline is adhered to, then new product introductions can

[12] IDA interview with GE Global Research executive, August 26, 2011.

be much shorter and costs will be substantially lower with a more reliable introduction of the product. Within GE, this is something that has been learned over and over again.

> When we have backed off this rule there have been bad experiences. Now we know this works and we're successful so there is good adherence to separating NPI and NTI and there is a lot of focus on determining that technology is sufficiently mature before it goes into a product.[13]

Project Management

GE uses a rigorous "tollgate" project assessment process. To make this work, it is essential that success criteria be defined clearly upfront. There is an ethos that it is better to kill projects early if they are not likely to succeed. "Within GE we are challenging programs all the time. Even if a project is in the OP Plan, if it is off plan we will stop or redirect it."[14]

One concern is that over time tollgate processes can become too bureaucratic. They usually start lean, but often more criteria get added, which can bog the process down and make it cumbersome. It takes discipline to keep the process tight and lean and it takes good people to make the process work. A focus on a set of key elements is needed with oversight to keep the process from collapsing under its own weight.

As research organization [as opposed to a development organization], GE Research expects that 80 percent of the research will fail—that is, will not make it into a development program. Research projects will be stopped either because the technology won't achieve what is needed or it is have determined that the market has changed and the technology is either no longer needed or cannot meet the new market need. At GE Research, success is not just getting a project done simply for the sake of completion—it's making the right decision on effectively utilizing resources… If a technology development will not achieve the required [specified] results, then "success" is killing it sooner rather than later.

GE Research focuses on research in the range of TRL 3 to 4—it is generally understood that this entails more uncertainty and higher risk than R&D conducted at the BU level. Thus it is recognized that success is not just getting through the tollgate, it is determining whether a potential technology should get through based agreed upon tests and criteria. This approach relies heavily on two important facets underlying R&D at GE: First, establish clear expectations of success factors upfront during development of GE's Growth Playbook process, Op Plans and "T Process." Second, hire the right people and incentivize good decision-making and teamwork.

This approach required a complete culture shift within the research organization: "we needed to inculcate that we should celebrate learning"[15] rather than simply getting through the

[13] Ibid.

[14] Ibid.

[15] Ibid.

tollgate process. This places an important role on management feedback in the research process, including performance reviews. The performance review sections on value and performance and the researcher's goals and objectives need to reinforce this perspective. The researcher should be given clear credit for having assessed whether a particular approach either worked or did not. The researcher should be able to state "I did this and this was of value since from this research we learned that it should be killed and then I was able to work on something else."

The earlier the TRL (3 or 4), the more failure is expected. However, by the time a project gets to TRL 6—failure is a bigger issue, raising the issue: How did we get here? The toll gate process needs to explicitly identify for each phase what needs to be done before moving to next phase—or what risk remediation must be taken. Adherence to the tollgate process must be rigorous to avoid "technology creep."

Multi-generation Plan–Product / Process

Regarding the question of how GRC balances near-term versus long-term R&D, GE cited three factors: 1) the effects of the people and processes inherent in multi-generational technology and product plans; 2) the structure of decentralized R&D at the BU level and centralized R&D at the corporate (i.e., GRC) level; and, 3) funding and different time phases for advanced technology development.

GE Research does not have the equivalent of a Defense Advanced Research Projects Agency (DARPA)—it is more focused on the "middle chunk" technologies that are more near-term (higher TRLs), but are generally beyond the focus of the business units. The Research Lab provides technical options or opportunities that are beyond the purview of the business units. Because of their near-term focus, the business units aren't aware of all the opportunities.

In the last ten years, there has been increased focus on overcoming a *second* "Valley of Death" that involves maturing manufacturing advancements before transition to full scale production operations. The problem has been that the lab researchers transition new products and technologies to established production operations that lack the capability to mature needed manufacturing processes. To help mature needed manufacturing processes, GE has established manufacturing Pilot Development Centers (PDCs).

GE established its first Pilot Development Center in New York for developing manufacturing capabilities for batteries. Since GE did not have a BU to host its fledgling battery business, GRC incubated a BU to support this business in 2009. The pilot center was supported by a mix of Global Research and BU funding. The funding is weighted such that the closer to production, the more the funding comes from the business unit. The pilot production effort does introduce some risk as it is developed at same time as technology issues are being examined at the TRL 5–6 level.

The battery business is probably the first organic business started up since GE Plastics. The battery business grew out of an appreciation of potential market adjacencies and new space. The need came from GE's locomotive business, where no appropriate energy storage technology could be identified. But it was also seen that there would not be enough volume in the locomotive business and thus for the rail transport need to be met, the technology would have to scale into other markets, such as telecommunications and other mobile applications. GE is now looking at a similar startup effort for solar energy.

A second PDC, the Michigan Advanced Manufacturing and Software Technology Center, was established late last year to "help GE develop innovative new software, processes and technologies to make our manufacturing businesses even more productive and competitive."[16] The center is focused on information technology, clean energy, and transportation.

Measuring and Metrics

Metrics for R&D are difficult: How to measure innovation is not easy and you get what you measure. Measuring R&D as percentage of revenue is problematic—R&D might be 3–4 percent of total revenue, but what is significant of this if a large proportion of the revenue is from the finance business, which relies relatively little on R&D? From a business perspective, one can look back twenty years and see where the company didn't stay up and lost a major business area (but that does not do much to support how much or where to invest today). GE's product mix has changed substantially from five years ago, but how much can this turnover be attributed to having successfully exploited R&D? It is appropriate that shareholders ask "What we are getting for the R&D that is invested." But how to demonstrate this is unclear. There are clear examples that describe how R&D overcame a particular need or created a specific opportunity. But going from such examples to metrics is difficult.

Organization Structure

Within GE Global Research, a Technology Director will have four to eight technology leaders, and globally, each leader has four to eight labs. The technology leader oversees the labs locally and reports to the Technology Director; otherwise there is not enough oversight and interaction to keep the labs healthy. This also allows the labs to have faster response to local opportunities. Eight to ten years ago in the device area all the labs were co-located—devices, structures, materials for devices… These grew with the success of digital x-ray as well as other technology thrusts, such as packaging, application-specific IC (ASIC) development, etc. Over time, there was critical mass to separate labs and this did not happen all at once.

Measurement of Results

A key measure of success for a lab is whether the BUs are becoming more connected with the lab. What research is used by the business units? What is return funding from the BUs? Are

[16] Ibid.

business units consistently engaged with the lab to develop next generation technology? How many projects got to NPI transition based on what the lab developed?

For researchers, the challenge is to shed technology areas to move onto new technologies or reshape the existing ones to tackle new applications and market challenges. This requires on an ingrained spirit of discovery with a sense of innovation and urgency. So their motivation should be to get the old stuff up or out and move on to a new development.

Technology Transition

GRC researchers will move to a BU with the technology as a bridge assignment, if the BU and researcher agree on this. In a bridge assignment, the researcher is part of the NPI team or business unit team. Even if not on a bridge assignment, the researcher is expected to support the business team when there is a critical need or problem. This can be as little as consulting and as much as 'Ready-To-Serve' projects where the researcher helps the team for several months to resolve a specific problem. It is frowned upon for GE business units to use GRC researchers to do the NPI work on a consistent basis. GE Global Research staff is comprised of researchers, not development engineers and it takes a different mindset to execute in an NPI domain for long periods of time. GRC does not want to lose the research talent. The business unit will have to pick up and resource the NPI if it is to succeed.

Partnering

How do government and industry coordinate in investing in a technology? A digital x-ray factory is an example—a large capital investment was required and the GE business could not afford this. GE worked with the government to support the technology in its early life cycle. The team was able to retire the technical risks and put in place the pilot manufacturing line to prove manufacturability. This line was transitioned to the GE Business this year after nine years in production at GRC.

GE MicroSystems and MicroFluidics Laboratory

As an example of GE's research process, the IDA study looked in more depth to GRC's MicroSystems / MicroFluidics Lab, which does considerable research into micro-systems and micro-electromechanical systems (MEMS). GE is not a MEMS company (though some of its businesses do manufacture MEMS-based products) but it seeks to use these devices in a broad range of applications throughout its businesses. The primary role of the research center is to look for solutions for such devices when they are needed. The center tries to solve problems by finding off-the-shelf components if possible. In the case of certain MEMS devices needed for specific customer needs, after an exhaustive search if no supplier is found or no foundry is willing to take on manufacturing the needed devices, then typically GRC labs will to try to develop the device up to TRL 4 (or beyond) and then go back to foundries to see if they will make it.

This is an example of GRC working directly with the business units to provide technical options to meet their needs. GRC will work with them to develop specifications of the needed device or component—technical details in depth—and identify alternative technology solutions (e.g., five to six) to solve problem. Then based on various trade-offs, GRC will recommend to the business unit how to solve the problem. There are multiple methods ranging from internal development to external acquisitions. Acquisition needs are usually developed by the business teams and they request GRC's participation in the assessment process. For internal development, GE businesses will have to fund GRC to develop it or GRC and the business unit can work to find other resources, such as government funding, to support the development (or it may be deemed too costly to pursue further). From this perspective, GE Research is hyper-sensitive to BU needs in performing this technology scouting and technology due diligence functions.

Certain business units within GE have a strong interest in MEMS devices. GE Measurement and Control Group, within GE's Energy Systems Group, bought Lucas Novasensor MEMS in 2004 from TRW. The acquired company produces pressure sensors for medical and automotive applications. GE subsequently bought Druck MEMS pressure sensor producer. Also in the early 2000s GE Research began research on MEMS-based sensors, but the acquisitions signaled a thrust in the use of MEMS as a business focus.

Subsequently, GE Research explored the health care opportunity of microfluidic devices. These are different from the pressure sensors as they are not based on silicon technology. Other applications the research group has explored include flow and gas sensing microsystems and metal MEMS processes. The use of the MEMS devices has been fostered by the Session T mechanism that brings business units together with the technology developers to exchange ideas connected to the businesses. As the hub for technology, these sessions provide a means to explore other needs within GE and to keep R&D group funded.

Some GRC labs are very closely tied to BUs and some BUs don't make much use of GRC labs. Most GE labs are very tied to businesses with detailed roadmaps. Other technology areas, such as MEMS are less directly tied to business units and have freer rein to pursue what is needed in future. But to do this, the research group has to spend effort looking for funding outside of the business units. Thus, GRC's Microsystem lab will go to universities, start ups, and some targeted government research for funding (sometimes with other groups that are more closely tied to BU's). Currently microfluidics is 80 percent government funded with the remainder corporate funded. It is targeted to reach 50 percent government and assessed and 50 percent BU contract research. A goal would be to develop suppliers as partners for BUs.

A key performance metric with Global Research is demonstrating value to the business units. A key measure is the group's ability to attract resources from the assessed funding and directly from the BUs—what are we paying back to them. Examples of payback include the digital x-ray fabrication and the new solar line which will be produced by GE's Prime Star.

Summary of Findings

- GE utilizes both centralized and decentralized R&D.
- GE R&D is open to sourcing solutions externally as well as developing internal solutions.
- GE works to balance short and long term R&D through funding and planning actions.
- GE R&D is highly customer (business unit) focused with some more speculative R&D pursued in GRC.
- GE works at leveraging R&D resources and outcomes across its enterprise.
- GE has placed considerable effort and discipline into implementing and adhering to its NPI and NTI planning and execution processes.
- GE seeks to avoid transitioning immature technology and concurrent NPI and NTI.
- GE is concerned with and invests in manufacturing aspects of technology commercialization.
- GE commercialization is implemented jointly by technology developers and BU operators.
- GE commercializes developments both internally (e.g., BUs and GRC) as well as through external parties (licensees).

IBM

A key focus of IBM Research is its Global Technology Outlook, which was started ten years ago with the idea of looking five to ten years into the future. Experience has shown that this focus should be more on a five year horizon, that ten years is too long. IBM was specifically seeking to identify "where are we going to go in the future?" and setting technology goals ten years ahead. But to do this, IBM determined it needed to have a perspective on where technology will be going. Based on this perspective, IBM "will make big choices on areas in which to focus."[17] Rather than focusing on notions of basic and applied research (e.g., 6.1, 6.2, etc.), the focus is on a set of portfolios with an evolutionary path in these. These portfolios are under the Director for Research, but cascade down with a VP for each portfolio thrust—such as materials science. From the top-down, the focus is on "Where do we want to go, and where can we lead." Corollary to this is "What should we stop doing?"

IBM Research has evolved from a traditional independent Research Lab in the 1970s to a greater focus on a clear link from R to D to manufacturing. The economic recession in 1982 forced IBM to focus on "tightening the ship" with a greater emphasis on connecting R&D to business results.

In the 1990s, IBM made a change in focus to go beyond and outside of IBM to link to others—especially leading edge customers in various customer sectors. IBM assessed who were the best clients with most demanding needs. Who could IBM partner with to develop an understanding of their needs and create leading edge solutions? One early partner was L.L. Bean, who was exploring Internet selling in the 1990s. IBM partnered with Bean on developing its website. Other lead partners include Bank of America, the New York Stock Exchange, and General Motors. This type of collaborative research is extremely important to IBM.

However, with this series of transformations IBM still does basic research. "If we want to understand phenomena and create we need people who are part of the scientific community."[18] Cannot just be the recipient—must play a role, know the best scientists, help shape the science to be useful. An example of IBM's involvement and commitment to science is the Semiconductor Research Corporation, which it helped create.

IBM has always considered the Federal Government as being an important partner, starting with the initial social security system in the 1930s, to its involvement with DOD during World War II, to its work with NASA on the space shuttle. These were more than just customers: they were research partnerships, which provided IBM extremely demanding technical challenges, with high levels of complexity, and were capital intensive. Today IBM has government partnerships across the civilian, defense, and intelligence arenas.

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[17] IDA interview with IBM executive, July 28, 2011.

[18] Ibid.

IBM also has research partnerships with foreign governments. A major concern is that IBM is finding that it is much easier to work with foreign governments than with the United States.

Government plays a crucial role as a catalyst of emerging technologies. This stems from its roles as 1) an early-stage procurer of new technologies that helps bring them to scale; 2) a policy-setter through regulation, defense policy, and industrial policies; 3) a user of technologies—promoting their implementation; 4) a maker of "big bets" on technology. Very few organizations can make these types of bets, and if the Federal Government doesn't, this leaves a major gap.

Big companies are crucial to the implementation of emerging technologies. They have the technical expertise and the program management capabilities. Small business and academics have niche knowledge in specific technologies, but not the scope of knowledge and the practical implementation skills. Therefore, while small businesses are a good means to seed new innovations, they rarely can bring them into fruition.

IBM emphasizes that it is one of the very few companies that makes big bets in technology. One example is its continued interest in parallel computing and supercomputers or more generally extremely advanced large-scale computing. This has included supercomputing for managing the nuclear stockpile for the U.S. Department of Energy (DOE); Deep Blue in 2000s—the genomics computing in which IBM invested over $100 million; and the most recent Watson cognitive understanding computer. Another example is the focus on trusted integrated circuits with Intelligence Advanced Research Projects Activity (IARPA) and others. The concern is that other governments are interested and willing to put big money on big new thrusts—including Saudi Arabia, King Abdullah University of Science and Technology (KAUST)—to buy equipment and computers; research labs in Brazil, and research in Australia. Governments are willing to put up $100 million and act quickly.

Operationally, the technical frontiers focus of the Global Technology Outlook translates into research projects. It provides the overall vision: Where are markets going and do we want to be in this? From this, problems and challenges are identified, which then leads to focusing of resources—money and researchers. Metrics are used to evaluate success and risk. Portfolio assessment is done to determine whether the R&D is focused in the right areas—areas that are projected to be future markets. However, IBM also evaluates research based on 1) patents—creating patents and the utility of the patents including income derived from them; 2) publications in recognized technical journals; 3) external recognition—such as selection to technical organizations, etc.; 4) whether the portfolio of the research group is meeting the needs of product groups and being incorporated into products with demonstrated value. Research managers, as opposed to bench scientists, are evaluated on "what's the impact of this research for the corporation."

R&D is seen as core to IBM's success. About 10-15 percent of IBM's R&D is basic research. IBM still values science and sees science as being critical to posturing itself for the future. In this sense, IBM maintains a long-term perspective and sees science as a being a key means to providing "the capabilities needed to create future leading edge technology." To this end, IBM sees semiconductors as a strategic technology and business that it will continue to develop. Leading edge ICs enable capabilities for high-end systems that IBM can "wrap services and applications into."

IBM has committed to open innovation and R&D partnerships. Twenty-five years ago, the IBMs ethos was "we can do it all. Now, we don't want to do it all: We cannot afford it and there are a lot of smart people out there that we can and need to draw upon." SEMATECH is an example of this new philosophy. The three dimensional integrated circuit (IC) program is open innovation—fifteen companies in a consortium working with NIST. X-ray lithography is an example where IBM independently attempted a large scale-endeavor that failed because it could not attract the rest of the community. IBM was too isolated from others in the industry and could not effectively implement this extremely costly technology. Therefore, IBM's sees collaborative R&D working in strategic partnerships as a crucial strategy for its future. Thus, collaborative programs with exchange of ideas among "smart users" are seen as being of great importance. From a strategic perspective, DOD should recognize that technology companies look for able, creative, leading edge partners and have valued DOD as such a partner.

Intel

Overview

Intel's research and development (R&D) expenditures in 2010 were $6.6 billion (up from $5.7 billion in 2009 and 2008). This was 15 percent of $43.6 billion in corporate revenue in 2010. Notably these increased R&D expenditures were in a recessionary economic period. Intel maintained the ratio of 16–15 percent throughout the past five years despite fluctuating revenues (ranging from $35.1 billion to the 2010 high of $43.6 billion).

Intel is an integrated circuit (IC) design and production firm—it designs IC products to meet different computer and related information technology (IT) systems customer needs, such as for desktop computers or mobile applications, and it produces these chip devices in its own production facilities (fabs). Its leading customers in recent years have been Hewlett-Packard (HP) and Dell, which together comprise 38 percent of Intel's sales.

How does Intel manage the process of basic research through to product development?

Intel Core Competencies: Architecture and Manufacturing

Historically Intel has been cautious about developing its own R&D capabilities. Its founders—especially Andy Grove and Gordon Moore—were concerned that an internal R&D organization would create technical approaches that the R&D organization would force onto the company's product or production process as opposed to having the processes defined by the customer's problems. Their concern was that the lab would promote its development of, for example, a particular resist for the integrated circuit production process to use, instead of evaluating outside suppliers' resists, which might be better suited to meeting the needs of the production operation. The focus of Intel has generally been to go to the outside for new technologies, such as to Stanford University or Sandia Lab, or through collaboration with consortia such as SEMATECH, but have a very facile means to further develop and integrate these innovations into its internal product and process development. Thus, Intel can be thought of doing open innovation from the beginning.

Intel sees its strength as understanding the big picture for developing and implementing the technologies rather than inventing them. One way they put it is "we see the blue dot that others don't"[19] in what a new technology can do, since Intel looks at it from an integrated production process perspective, not as an individual technology in itself. Consortia and universities, etc., focus largely on individual process steps, but companies, such as Intel, are better positioned to do the integration of the steps.

The innovation process at Intel has become a carefully managed iterative cycle of product development and process development: which Intel calls "tick tock." The product design aspect

[19] IDA interview with Intel executives, July 11–13, 2011.

of Intel is organized under its Intel Architecture Group (IAG) based on product areas. Because of the criticality of manufacturing processes for sustaining its competitive position, Intel places a great deal of emphasis on developing production processes and manufacturing technology. The production process is organized as the Technology and Manufacturing Group (TMG). TMG operates Intel's fabs that make the products for IAG.

Product R&D

Intel Architecture Group (IAG)

IAG product development and architecture focuses explicitly on silicon-based IC devices. Within IAG, there are the following Product Groups: Data Center (Server), PC Client (Desk Top Systems–DTS and Mobile), Ultra Mobility, Embedded and Communications, and Digital Home and Visual Computing. Each of these product groups focus on external customers, primarily computer manufacturers.

The architecture and design group within IAG explores new product areas such as cloud or graphic applications through different ways of integrating functionality on the IC as well as within systems. The focus is three to five years out.

Intel sees itself as a horizontal company: as an example, the Data Center (Server) group seeks to build product platforms across the range of datacenter applications and even workstations—"We try to build vertical product layers across segments."[20] (In contrast, Apple's focus is very specific to vertical market areas (verticals), such as entertainment and education. Apple does a lot development work on operating systems that can even be considered to be applied research.)

IAG's R&D explores usage from the perspective of end customers—beyond immediate product customers such as Dell and HP—to such end-users as the oil and gas industry (which has massive data processing as well as modeling and simulation needs) or the search applications developers. From these users, IAG identifies user needs, such as the types of instructions they want, power management, or cost of ownership.

In introducing new capabilities on an IC, Intel seeks to minimize risk. In particular, it carefully orchestrates the introduction of new architectures for chip functionality using the current generation of process technology and will then move that architecture to the next generation new process technology with minor changes. Then the next year, it will introduce the new generation architecture on this now current process platform.

Intel stresses that when it puts something into a new chip architecture, it is not a gamble—it has been carefully developed and assessed to be assured it will work both technically and from a

[20] Ibid.

cost standpoint. “Real risk is done on the side.”[21] For example, Intel does develop its own algorithms for on-chip processing. But before these are introduced onto a chip, they are carefully evaluated. Basically, if its performance has not been fully demonstrated, the algorithm won’t get into the current design cycle.

Intel has staggered processor design teams. It takes approximately five to six years from initial concept to a finished chip. Therefore, in each product area, Intel will have three overlapping teams. For any new chip project, there is “significant risk assessment at front end.”[22] If a high risk concept is being explored, it will be assigned to a separate team to take on the risk. A new chip effort will take on no more than one or two new areas of risk. Anything more will be delayed until the next product iteration. All developments are evaluated through a risk assessment regarding how much this will affect the schedule using decision-based algorithms with sophisticated modeling tools that evaluate how it will perform; whether there are bottlenecks; its dependencies and how to mitigate the risks. For these assessments, Intel uses mainly home-grown proprietary analytic tools.

Some key technical constraints that IAG has to work within are die size and instruction word length. Die size has grown over time, but within a particular die size, the architecture group has to determine what functionality they can get on the chip and what to cut out. This requires they work with customer end-users to keep them informed on what features can be incorporated. (Basically this requires an iterative process of customer communication on what is technically feasible under these constraints versus what the customer would like to get in performance and functionality.)

Over time there have been shifts in instruction set word length, which can be disruptive for the customer, as well as technically risky. This change in instruction sets (such as going from 32 bit instruction to 64 bit instruction) is a major design challenge because while the underlying machine is much different it still must execute they way it did before and not break features of prior technology.

The chip design process determines platform optimization points, which define the set of features for this product cycle. The features desired are traded off in engineering analysis of permitted cost and schedule requirements. Once this has been determined (negotiated) no more new features are allowed. This highly disciplined process has vastly improved Intel’s success in meeting product schedules. In the past, Intel was canceling 50 percent of its product development projects. Now 100 percent of it projects are on time and within budget. Intel has adopted the philosophy that it is better to have something out on time that works, but is good enough in terms of performance features, than to attempt to be overly aggressive on adding performance, but miss product schedule or cost constraints. (In essence, Intel sees the iterative product design cycle as never being 100 percent perfect from the standpoint of performance, since new features and

[21] Ibid.

[22] Ibid.

capabilities can always be conceived. The key question is what performance can be achieved optimally within a particular design cycle without sacrificing cost and time metrics.)

Improvements in performance are achieved by both developments in architecture of the product and in processes for chip production. One example on the product development side is the development of algorithms to minimize data movement in order to speed up chip performance. The performance of the algorithm will be evaluated using device models built into simulators, which assess how things are moving to get the performance. Based on these models, the designer can remap the algorithm or a try a different structure to move data closer to where it is needed. However, the device models may not be sufficiently accurate to provide exact results, so before a specific a function is moved over to design, it is evaluated in test circuits.

Intel's IAG does applied R&D around the entire platform of computing systems, as well as explicitly on the integrated circuit device products. One example of this type of systems-oriented development work is R&D on thermal problems with computer systems. This is not something that Intel would sell to customers. Rather such research is seen as supporting the customers' ability to advance their products and provide pathways for future integrated circuit products. Intel sees this as supporting innovation through the computer-information technology industry and that Intel has a unique ability to understand the entire system as part of its design of the chip and chip sets. Because of its focus on product planning several years out, Intel has broad insight on where industry is going. As a maker of the primary components needed by the information technology systems developers, Intel wants industry to push the envelope in capabilities on such characteristics as size, weight, and battery life to drive innovation, and through innovation, shape product demand. Intel sees this as system and subsystems co-optimization and development. "As chip makers we need to support innovation in rest of platform."[23]

Intel tries to anticipate and conduct R&D on future trends and opportunities in IT systems ahead of and in conjunction with its customers. One example is its R&D developing technologies to develop extremely thin laptops. This research encouraged industry and provided underlying technologies that enabled these to be developed, and because of that R&D, Intel was ready for these products when the customers moved to them. Thus, IAG researchers develop platform oriented approaches that look at future potential needs: if there are thinner laptops, they research not only what would have to happen to chips, but also what would be other needs, such as thermal implications. Thus, Intel's IAG has done research on thin laptop skins and how to better cool the laptop with new types of fans. One result of this research is laminar wall jets technology for thermal solutions. This entailed changing chassis design of the laptop, not the chips themselves. This technology for achieving cooler, thinner laptop systems takes the stress off cooling the chips in such systems, which promotes better reliability and also a better product from the end-customers standpoint—one that is comfortable to use while being substantially lighter.

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[23] Ibid.

In IAG, a key source of platform challenges is through interaction with customers: "We see their pain points—can we solve them?" Potential problem solutions are identified through various means including exchanging ideas through Intel's internal network and collaboratively at the technology leadership level—these processes are both informal and formal—for some explicitly defined problems Intel will organize formal internal conferences and will also search for ideas externally including universities, setting up collaborations, etc.

IAG does employ, within its product areas, processes for casting a wide net for possible solutions and then filtering these down to a few that are assessed to be feasible and most likely to meet the customer's need. However, Intel managers strive to keep the gate-process as light as possible and minimize its burden on the researchers. Intel research managers want to encourage innovation and make sure the research is aimed at innovative solutions by pushing (encouraging) risk taking at the front-end with the prospect that only one in twenty ideas will make it through—the view expressed is "to fail often, early" with assessments providing a means to identify and select the most promising approaches for more focused development.

Technology transition for IAG's systems-focused research is case by case, depending on the type of technology and how it relates to specific customers. Because Intel sees it in its interest to promote innovation in end-product information technology systems, it will often work with a customer—devoting sometimes people-years of effort—often in close collaboration. In moving the systems technology out to the customers, Intel will pursue many different paths, which gets into sensitive business relationships. This represents a somewhat unusual, if not unique, relationship in technology development: Intel is the supplier doing R&D primarily aimed at helping its customers. From Intel's perspective, this R&D provides a balance—"they can use the results and we benefit."[24]

Process R&D

Technology and Manufacturing Group (TMG) is the organization that produces the IC products designed by the IAG groups. TMG has under it the design rules, technology roadmap, manufacturing, suppliers, and process "R&D out to the horizon beyond the headlights."[25] Its focus is only silicon production processes.

The foundry concept is relatively new at Intel. This is a new structure that evolved as the "virtual factory." This is a highly structured layered set of processes that is aimed at developing an integrated manufacturing process for a fab that is totally and exactly replicable such that the chips produced in one fab are exactly the same as (and indistinguishable from) those from another. The need was for the chips from different fabs to be identical to the customer (e.g., HP or Dell) that they would accept chips from any Intel fab with only one qualification. This was a major cost savings to Intel.

[24] Ibid.

[25] Ibid.

The development of the next generation fab processes results from R&D that feeds up through several layers of R&D organizations. Top down from current production to longer-term process development, Intel's production operation falls into the following organizations:

- Fab-Sort-Manufacturing (FSM)—FSM is responsible for Intel's worldwide wafer fabrication facilities that manufacture microprocessors, micro controllers, flash memories, chipsets, and other devices.
- Portland Technology Development (PTD)—establishes the next-generation processes to the first fab (also has labs for process forensics).

Intel works collaboratively with external R&D organizations and partners including SEMATECH, IMEC, and the ITRS process. It monitors research at universities and under the Intel Science and Technology Centers funds university research (see discussion of Intel Labs, below). By fostering close linkages to Intel's internal component labs, Intel R&D pulls these external developments inside through its PTD organization within its TMG. In PTD, half of the researchers are on loan from its production facilities (fabs). The processes developed by these R&D teams are incubated into the fabs. Intel emphasizes that this is not a handoff; rather it is a direct infusion into the FSM organization of TMG which operates the fabs. A key aspect of this is the transfer of personnel who helped develop the process from the PTD back to the fab.

In production process development, Intel's PTD supports two overlapping teams—one working on the next generation process and the other on the plus one generation to leapfrog it. A fundamental tenet of Moore's Law: It's profitable to innovate. But to meet the time cycle constraints, Intel needed to develop a seamless path to high volume production with R&D to push continuous process improvement.

On the production process side of Intel, they do not do a strict stage-gate process (but they do on the product design side in IAG). The reason for this being that process R&D is highly based on overcoming technical risk as opposed to the question of being implemented if it works. Basically the R&D is driven by the process R&D roadmap. Thus, process R&D can plan on a more predictable schedule in contrast to the product development process, which has to consider a broader base of effect uncertainties in terms of whether the new device design can meet customer needs, etc.

Technology Manufacturing Engineering (TME) is responsible for the technology strategy linked to consortia including SEMATECH, IMEC, and ITRS. Dr. Paolo Gargini is the Director of Technology Strategy. Tech Strategy has a staff of about fifteen fulltime and around forty to forty-five staff members that rotate in and out primarily onsite at consortia and external research organizations (e.g., IMEC) on a three year cycle (as a TMG policy). Universities were under TME but moved under Component Research (CR) to be closer linked to the customer… (the part of Intel that deals with outside technology.)

> The TME puts together different mindsets—the more innovative technologists with the process engineer.[26]

Component Research (CR)—Mike Mayberry, Director—develops the potential processes for the future fab.

> Components Research is the research arm for the Technology and Manufacturing Group of Intel… responsible for ongoing research to enable future process options for Intel's technology development organizations. This scope includes internal research, external university research, and other external collaborations.

At Intel, Mayberry's focus is on process R&D—"anything that we might put into our factories." He mentioned that Intel's approach to R&D has evolved greatly since the 1980s. In the 1980s, Intel had a very small internal process R&D group that focused primarily on "gap filling" of the current process and also some focus on university research. After twenty-five years, both of these functions have grown substantially—and Mayberry has them both under him.

Process R&D is divided into three phases:

Near-term—3–5 year horizon—the last 10 percent gap-filling engineering of processes—performed essentially all internally.

Mid-term—5–7 years—Option development applied research based on a product, unit opportunities, such as a data rate need that might require optical interconnect, or process challenge that might require innovation, such as a structure that when miniaturized might be too weak and thus require some new approach. Mid-term research is mostly internal.

Managing risk at this stage is crucial—Intel will usually explore two approaches: one that is higher risk (technical and implementation risk—cost and time), but more capable, and another that is less risky, but less capable. At this level, Intel is achieving about 50 percent success—which is also the level that they have targeted. (For near-term, the success is "always" 100 percent moving into production—doing whatever it takes to achieve this.)

Longer-term R&D—beyond seven years. This is mostly done outside of Intel either in universities, in consortia, or with research partners.

An example is the development of the tri-gate transistor to overcome gate leakage. This had a long incubation (about a decade) in outside research—primarily academic research and through consortia (such as SRC), followed by a ten year development within Intel. Concurrently, Intel was supporting external research on Hi-k dielectrics to deal with channel leakage.

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[26] Ibid.

Intel Labs and CTO

The Intel Labs operates separately from the product and production groups under Director of Intel Labs and CTO Justin Rattner. Intel Labs under Rattner does not support the current business groups and does not do R&D on silicon processes. The focus of Intel Labs is longer-term—seven to ten years out. Intel Labs looks further out in time and more on the potential future uses and needs for computing capabilities, than on specific integrated circuit designs or processes.

For example, at the 2010 Intel Developers Forum, Rattner discussed a specific thrust of his organization: *Context Aware* devices.

With computing devices having increased processing power, improved connectivity and innovative sensing capabilities, Intel researchers are focused on delivering new context-aware user experiences. Context-aware devices will anticipate needs, advise, and guide a user through their day in a manner more akin to a personal assistant than a traditional computer. Context aware computing, via a combination of hard and soft sensors, will open up new opportunities for developers to create the next generation of products on Intel platforms.

Rattner also presented Intel's interest in developing increased security in interactive devices:

> While we're developing all of these new ways of sensing, gathering and sharing contextual data, we are even more focused on ensuring privacy and security as billions of devices get connected and become much smarter." Rattner said. "Our vision is to enable devices to generate and use contextual information for a greatly enhanced user experience while ensuring the safety and privacy of an individual's personal information. Underlying this new level of security are several forthcoming Intel hardware-enabled techniques that dramatically improve the ability of all computing devices to defend against possible attacks.

Rattner presented the ultimate example of sensing—a human brain-computer interface. Through the Human Brain project, Intel's aim is to enable people to one day use their thoughts to directly interact with computers and mobile devices. In a joint project with Carnegie Mellon University and the University of Pittsburgh, Intel Labs is investigating what can be inferred about a person's cognitive state from their pattern of neural activity.

Intel Labs also sponsors several Intel Science and Technology Centers designed to increase university research and accelerate innovation. The current centers are for visual computing, secure computing, cloud computing, and embedded computing research.

Proctor and Gamble (P&G)

Proctor & Gamble defines itself as an innovation-driven company. Specifically P&G only chooses to play in categories where innovation is a differential driver of purchase intent. The motivation for P&G's emphasis on R&D management stems from:

- The value of the development of new products—corporate growth has depended on bringing new products market faster than its competitors.
- The open innovation process, which allows P&G to actively identify potential partners and attract potential partners (called Connect+Develop—see Huston and Sakkab, 2006.)

P&G's open innovation strategy for new technologies (products and processes) is based on a two dimensional grid with four quads that considers:

1. Is this technology/expertise/capability critical for competitive advantage?
2. Is P&G best-in-class in this area, or is someone outside of P&G best-in-class?

When the answers to these questions are both yes, P&G will link the potential new development to its existing competitive advantages that are supported by current core competencies. If the answer to (1) is yes and (2) no, then P&G may look externally to identify partners that can help accelerate R&D so that P&G can develop best-in-class status in that particular area and potentially gain competitive advantage. Where links do not exist then P&G may consider options such as licensing a technology from some other firm and/or licensing a technology to another as an external partner. A key discriminator for P&G decisions is a judgment on whether P&G is or can become best-in-class in this product/process. If P&G is not currently best-in-class, can it access this capability outside of P&G? If it cannot be accessed outside, then P&G would need to develop the capability internally.

P&G considers both current needs and identified future challenges when considering R&D. This helps the company avoid path dependency that may come from only addressing needs in existing business areas. When considering needs and challenges, the company considers "a problem defined is a problem half solved."[27] P&G's intent in any technology pursuit is to be best-in-class. P&G's strategy is to maintain their best-in-class competitive position in the marketplace for key products and or technical competencies (e.g., shampoos) and decisions about investing in new areas have to support their best-in-class positions.

The process of defining needs and challenges is run out of CTO Bruce Brown's office with seven individuals who both work in the CTO's office and also represent the relevant P&G business areas. This group identifies the top needs for each business and also corporate-level platforms. P&G focuses on identifying and developing platform technologies, i.e., technologies

[27] IDA interview with P&G executive, July 6, 2011.

that provide value across the company that can support a host of existing business areas as well as potentially spawn new areas. The fact that these individuals represent P&G's core business areas is deliberate so that each area has "skin in the game" when identifying corporate R&D priorities. This also allows each business area to articulate specific needs and challenges during this process.

There is also a group that formally oversees an internal and external entrepreneurship venture fund for investing in products and ideas. The purpose of this fund is to incubate innovative ideas both from internal and external sources; however, an existing business area must see some value in the idea or product and demonstrate a willingness to take responsibility for it at some point in the maturation process.

The process for tracking potential new ideas is systematized in the Connect+Develop process. When ideas or innovations come to P&G from external potential partners, P&G assigns them a single point of contact. Each idea or innovation is logged in P&G system, and is tracked across a cascading series of screening and filtering processes until a decision point is reached. If the idea or invention passes through the screening process, licensing and intellectual property issues are addressed. P&G is trying to be more flexible in working with small start ups to meet specific needs.

In the Connect+Develop model of open innovation P&G aims to only spend money on things that work and therefore only commits to upfront investment in innovations that have been determined to be potentially valuable. P&G's goal in this strategy is to have 50 percent of innovation come from external sources. They have found that products from external sources have a two times net present value (NPV) greater than those that are internally sourced. This determination is based on a P&G assessment of return on investment from R&D, which the company does in a systematic manner. Part of the reason for the high NPV for externally sourced developments is the careful front-end assessment to only take on those where there is a high probability of return.

In partnering with universities to accomplish R&D objectives, the P&G experience is that it has been more successful working with foreign universities than U.S.-based institutions and that P&G was more successful partnering with universities on specific tasks rather than longer-term (three to five year) projects. This prompted P&G to complete a benchmarking study (eighteen months ago) that examined other leading firms' (e.g., Ford, Nokia, etc.) interactions with university partners and concluded that they: 1) worked with fewer university partners; 2) did so in a more concentrated and directed fashion; and 3) worked with university partners over the long-term. Results of the study indicated that successful university relationships included: 1) smaller numbers of university relationships (P&G had 300–400 projects underway); 2) longer term projects of three to five years; 3) board level involvement; and 4) university projects/partnerships tied to corporate strategy. These results drove P&G's decision to partner with Michigan, Ohio State, Massachusetts Institute of Technology (MIT) (and several other universities under discussion) and to target top science and engineering professors and labs rather than simply giving money to each university or department to allocate. Additionally, P&G is partnering with specific university centers in such areas as colloid science.

Regarding measures and metrics P&G uses to establish return on investment for R&D, the company places a great deal of emphasis on customer satisfaction and has several methods for evaluating whether R&D investments are leading to acceptable returns. P&G has a three–five–seven year forward projecting and growth model process. The company measures its growth in part by tracking how a new product contributes to overall growth through incremental sales (return/cost/sales).

P&G has a clearly articulated growth model that establishes benchmarks for how much the company should be getting out of R&D investments as measured through product sales. The company tracks and measures the entire life cycle of individual product lines and projects rather than looking by function, such as R&D or marketing, independently and trying to establish each segment's relative contribution to sales. The measurement process is guided by the questions, "How well did we do and how well did we say we would do?" To answer this, P&G looks back at their three year projections and tracks the real versus projected cost and time investments across the company's very disciplined stage-gating process. P&G's experience has been that the less they use their stage-gate process, the more failures they've seen.

An example of P&G's R&D is the Swiffer product line. The initial idea and technology came from outside of the company. A P&G employee saw some of the nascent technology while in Japan and brought it to the attention of P&G's internal venture fund where it progressed through the screening process. Although it was first perceived as not fitting in with P&G's existing business, it was determined that it might provide a complementary business prospect (adjacent market) building on P&G core competencies. The eventual product line built heavily upon P&G's core competency and ongoing R&D in substrate materials used in such products as diapers. The real challenge that the company faced was the market risk of whether P&G could drive "habit adoption" by consumers, and not technology risk. The R&D for this product was over a three to four year period using a venture capital (VC) approach.

P&G currently has a network of twenty-seven technical centers that the company currently operates. It plans to consolidate to sixteen centers in the near future. The goal is to focus on centers of excellence and scale up labs in certain key areas (e.g., life sciences and surface cleaning) that can serve more of P&G's development research (versus scientific research) requirements across multiple P&G businesses. The objective is to create truly cross-cutting centers that would act as hubs for a research, test, and development (RTD) activity with an emphasis on the development of platform technologies rather than pure research. This is one motive behind P&G's emphasis on establishing better relationships with universities and federal labs to perform scientific research.

Appendix B
Illustrations

Figures

Appendix C
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Appendix D
Abbreviations

AMAT	Applied Materials
ASIC	Application Specific Integrated Circuit
BIPV	Building Integrated Photovoltaics
BR&T	Boeing Research and Technology
BTSG	Boeing Technology Scouting Group
BU	Business Unit
CAPE	Cost Assessment and Program Evaluation
CEO	Chief Executive Officer
CIO	Chief Information Officer
COO	Chief Operating Officer
COTS	Commercial Off The Shelf
CR	Component Research (Intel)
CRADA	Cooperative Research and Development Agreement
CT	Corporate Technology (Applied Materials)
CTO	Chief Technology Officer
CVC	Corporate Venture Capital
CVD	Chemical Vapor Deposition
DARPA	Defense Advanced Research Projects Agency
DOD	Department of Defense
DOE	Department of Energy
DTS	Desk Top Systems
EBO	Emerging Business Opportunity
EM	Exxon Mobil
EO&T	Engineering, Operations and Technology (Boeing Company)
ETS	Enterprise Technology Strategy (Boeing Company)
FFRDC	Federally Funded Research and Development Center
FPD	Flat Panel Display
FSM	Fab-Sort-Manufacturing
GAO	U.S. Government Accountability Office
GE	General Electric

GRC	Global Research Center (General Electric)
GTC	Global Technology Council (Kraft Foods)
GW	Gigawatts
HP	Hewlett-Packard
IAG	Intel Architecture Group
IARPA	Intelligence Advanced Research Projects Activity
IBM	International Business Machines
IC	Integrated Circuit
IDA	Institute for Defense Analyses
IP	Intellectual Property
IT	Information Technology
ITRS	International Technology Roadmap for Semiconductors
KAUST	King Abdullah University of Science and Technology
LCD	Liquid Crystal Display
MDAP	Major Defense Acquisition Program
MDD	Materiel Document Design
MEMS	Micro-Electromechanical System
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
NGO	Non-government Organization
NPD	New Product Development
NPI	New Product Introduction
NPV	Net Present Value
NTI	New Technology Introduction
OP	Operations Plan
P&G	Proctor and Gamble
PAD	Program Authorization Document (Boeing Company)
PDC	Pilot Development Center
PTD	Portland Technology Development (Intel)
R&D	Research and Development
RDT&E	Research, Development, Test, and Evaluation
S&T	Science and Technology
SEMATECH	Semiconductor Manufacturing Technology
SME	Small and Medium Enterprise
SRC	Semiconductor Research Corporation
SVP	Senior Vice President

TME	Technology, Manufacturing, Engineering (Intel)
TMG	Technology and Manufacturing Group (Intel)
TRL	Technology Readiness Level
TS&E	Technology Scouting and Evaluation (Boeing Company)
UAV	Unmanned Aerial Vehicle
VC	Venture Capital
VP	Vice President

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14. ABSTRACT

This study reports IDA research on current commercial industry practices for organizing and managing research and development (R&D) with a focus on: "How does industry place its R&D bets and manage R&D outcomes to meet corporate goals?" Through literature review and interviews with R&D leaders at U.S.-based technology companies, the study finds firms have fundamentally refocused, reorganized, and rethought their R&D practices. Four themes are common: 1) R&D is managed for business results, even for exploratory projects; 2) Companies are increasingly accessing R&D from outside the company; 3) Technology thrusts are explicitly derived from a strategic perspective on aligned with business goals; 4) Technology development is a top-level corporate responsibility. Industry leaders measure and assess the results and value of R&D and manage the R&D process using this information, including: developing a coherent strategic plan; managing to get results out of the R&D process; broadening the sources of and integrating new ideas into the firm; measuring and assessing R&D results and value. Best practices include: corporate efforts to execute open innovation; stage-gate processes employed early and empowered to modify or terminate R&D efforts; transition planning addressed early in development with leading firms explicitly avoiding the transition of immature technology to production.

15. SUBJECT TERMS

Research and development (R&D), commercial industry, best practices, open innovation, stage gate assessment, portfolio management, technology readiness levels (TRLs)

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