PLANNING YOUR FIRM'S R&D INVESTMENT

"R&D Gain" can be employed as a tool for determining the size of the aggregate R&D budget required to meet the firm's growth aspirations.

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OVERVIEW: *Setting the level of R&D spending is one of the most important strategic decisions made by top management of technology-based firms. The delay between the commitment to expenditure for R&D and the realization of consequent revenues and profits complicates the analysis of R&D budgets. Common budgeting practices often fail to reflect the likely revenue consequences of incremental changes in aggregate spending for R&D. The authors suggest that this "missing dimension" should be incorporated in analysis of budgeting choices. They propose a framework for R&D budgeting and incorporate a measure of the missing dimension, named "R&D Gain," defined as the ratio of the lifetime revenue of products launched in a particular year to the total investment needed to develop those products. This Gain can be estimated from historical data on revenues and R&D expenditures, and used to project future revenues.*

KEY CONCEPTS: *revenue growth quantification, R&D Gain, R&D level.*

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R&D spending is a material component of costs and a strategic element of investments, representing from five to ten (or more) percent of revenues in technology-intensive industries (see Table 1). Deciding how much to spend on research and product development is one of the most important recurring strategic choices facing managers of technology-based firms.

This article describes common approaches to determining the aggregate level of R&D investment by large technology-based firms. The budgeting process used at Xerox is presented in greater detail, based on a decade of experience by one of us with R&D budgeting decisions. The article then proposes a framework for R&D budgeting that incorporates a measure for estimating future revenues given a certain aggregate level of R&D spending. This measure, which we call "R&D Gain," reflects the organization's overall effectiveness in capturing value from R&D through design, manufacture and marketing. We focus on established firms whose revenue depends on a continuous stream of innovative products that are differentiated in the market by new technologies.

Numerous academic studies examining the payoffs from R&D have found that there is a strong positive relationship between R&D spending and future revenue growth, and that R&D investment enhances shareholder value (*1*). These studies document the long-term benefits of R&D investments, thus arming the Chief Technology Officer to argue that more investment is better. But R&D is not an unlimited good thing; there is some level beyond which increased expenditure does not yield commensurate rewards. To quote John Armstrong, formerly vice president of research and technology at IBM, "you can spend too much on R&D" (*2*). Unfortunately, the CTO seeking quantitative guidance toward an optimum level of R&D spending finds little that is helpful. The methods described in this paper, while not defining optimal spending levels, will provide quantitative measures by which CEOs and others can appraise the adequacy of the R&D investment to achieve a desired revenue growth rate and evaluate trends in the firm's performance.

R&D Investment Analysis

Accounting rules require that the costs of research and development be expensed in the year they are incurred. The economic reality of R&D spending, however, is that it is an investment, in the sense that resources are expended in the current year with the expectation that revenues will be earned in future years. Within a given firm, the appropriateness of the R&D expenditures (i.e., the magnitude of economic returns) can be evaluated at various levels of aggregation. Our focus here is on the highest level, the aggregate total expenditure on R&D. A finer-grained analysis could differentiate phases of R&D (e.g., applied research, technology demonstration, and product development). An even more detailed analysis could involve allocations to specific categories of projects within each phase of work (*3*).

Common business practice brings four distinct, but overlapping and intersecting, sets of logic to bear on the determination of aggregate level of R&D investment. These can be characterized as involving, respectively, corporate financial boundaries, competitive benchmarking, product portfolios, and speculative future opportunities.

Corporate financial boundaries

A top-down business planning process drives this logic for determining R&D expenditures. Typically, this process involves development of an annual operating plan consistent with an existing strategic plan. Operating plans generally reflect continuity with the recent past. But, in some situations, they may incorporate discontinuous elements, such as strategic repositioning of a business, development of a new business model, establishment of new product lines, or fundamental changes in the character of the R&D activity itself. In either case, the operating plan establishes financial boundaries for revenue, profit, selling and administrative costs, R&D, and cost of product, generally within a 12-month planning horizon. In this logic, the budgeted scope and level of R&D activities will be adjusted to fit within the allocated financial boundaries.

Four distinct sets of logic bear on the determination of aggregate R&D investment.

R&D benchmarking

A second determinative logic is based on industry characteristics. Typically, the benchmark metric is R&D intensity (R&D spending as a percentage of sales). The rationale is that to remain competitive, a firm should make R&D investments at a level similar to that of other firms in its markets. Thus, one often observes that firms in a particular market tend to invest at comparable R&D intensities.

Product portfolio

In contrast to the top-down character of the first two approaches, the third logic involves a bottom-up analysis of specific investments required to compete through new products or services. The aggregate R&D budget is built by summing investments for development of future products. R&D line items may be influenced by whether the targeted market is growing or mature, whether the firm is a technology leader (competing on new function) or follower (competing on cost), or whether its competitive advantage is design, manufacturing or distribution. This approach often uses portfolio techniques, which balance growth, risk, investment amount, and timing of returns (*4*).

Speculative future opportunities

In some companies a fourth logic is applied to budgeting for long-term research aimed at creating future investment opportunities. Because the planning horizon is typically three to seven years, the targets are speculative and the research may not produce results until after the tenure of the CEO who funds it. The pioneering research activities supported by some technology-based firms exemplify this category.

The rationale for this sort of investment is based on the past achievements of central research laboratories such

Table 1.—R&D Intensity of Selected Technology-Based Industries in 2000.

All industries	3.4%
All manufacturing	3.3%
Chemicals	5.9%
Synthetics	5.6%
Drugs and medicines	19.8%
Computer and electronic products	7.9%
Computers and peripherals	6.5%
Communications equipment	9.6%
Electronic components	7.4%
Measuring and control instruments	8.0%

Source: *National Science Foundation—Research and Development in Industry—2000.* Table A-20. Company and other non-Federal funds for industrial R&D performance in the U.S. as a percent of net sales of companies that performed industrial R&D in the United States.

Steps in the Planning Process

- **Estimate past values of Gain for your company.** Using historical records of revenues and R&D spending, estimate past values of Gain. The simplified method described in the text can be used to develop initial estimates. Identify factors that may have caused Gain to change over time.
- **Competitive benchmarking.** Do the same for the firm's competitive cohort. Use comparative data to help identify factors that may explain observed Gain and R&D intensity differences among firms.
- **Estimate Gain value for near future.** For your firm, estimate the expected value of Gain for the next year or two, based on consideration of the current Gain value and trend over time, plus possible investments underway in marketing, sales, etc. that may affect Gain.
- **Project future revenues.** Use estimates of future Gain and planned or expected levels of R&D spending to project new revenues for the near future, then add revenues from legacy products.
- **Consider alternative scenarios.** Examine actions that might enhance gain, options for increasing R&D spending or shortening product development time to achieve greater growth in revenues.—**G.H., M.M. and R.R.**

as IBM's Yorktown, Lucent's Murray Hill, and Xerox's PARC (*5*). The amount budgeted for speculative research is typically 0.25% to 0.50% of revenue, and is often guided by a dialogue between the CEO and CTO that includes a review of emerging market and technical trends, recent technical breakthroughs, and their relevance to the business. Considerations include fit to the firm's business model, intellectual property, future investment options, and core competencies. Real options reasoning may be used to allocate resources to specific projects.

R&D Investment Decisions in Practice

The R&D budgeting practices of Xerox illustrated a pattern that we believe characterizes behavior within many large and mature technology-based firms. R&D is organized in two main parts: product development, about 80% of the total, is planned and managed by the business divisions; the remainder is organized in research laboratories controlled at the corporate level, its size determined jointly by the CEO and CTO.

Xerox practice

At Xerox in the 1990s, the level of R&D spending was reconsidered annually as part of a corporate-wide operating plan process. It started in March with a strategic dialogue between marketing, product development and research groups, and ended in December with budget closure directed by the CEO. A bottom-up R&D budget was formed by summing business group requests for product development requiring one to three years, and central research laboratory requests for work on next-generation technology to be realized in three to seven years.

Based on current and anticipated business conditions, at midyear the CFO and the Corporate Strategy Office proposed P&L financial boundaries for the following year. Then, costs for various marketing, sales, manufacturing, inventory, corporate overhead, personnel, and R&D line items were adjusted to achieve the financial targets. Once the year began, the R&D budget might be modified again depending on quarterly revenues and profits. These cost adjustments were tactical; strategic implications were reconsidered at the beginning of the next planning cycle.

A key planning metric at Xerox was R&D intensity for the coming year, computed by dividing the planned R&D investment by the anticipated revenue. The R&D intensity was periodically compared to firms in the competitive cohort, and kept relatively constant year over year. A decision to increase R&D spending was usually tied to next year's anticipated revenue, with revisions possible depending on short-term affordability. This approach implicitly assumed that the R&D budget followed revenue and profit growth, rather than driving it.

Other practices

Interviews with CTO executives from IBM and Lucent suggest that the Xerox process was not idiosyncratic (*6*). Although the R&D investment histories of the three firms over the last 20 years are quite different, their budgeting processes were similar. Except for years in which the firms underwent strategic transformations (which happened to all three), each year's budget was essentially an incremental adaptation of the preceding year's portfolio. All were driven by a top-level strategic vision of the business, subject to the constraint of a profit plan.

What's Missing?

What impact do the four types of logic have on the final determination of the aggregate annual level of R&D spending in a technology-based enterprise? We believe that all four logics come into play at some point in the routine practices for R&D budgeting of many technology-based companies, including Xerox, IBM and Lucent. While the analysis of product portfolios and speculative opportunities can be useful to determine which specific investments, at the margin, are dropped or retained, these logics have limited influence when top management sets the aggregate level of spending for R&D. In most cases, when trade-offs of budget line items for the current year must be made, the dominating consideration is the logic dealing with corporate financial boundaries.

The R&D intensity benchmark often serves as a test of reasonableness that the level of investment is in the right range. Unless a comprehensive, bottom-up analysis of investment options is performed—with all the attendant uncertainty of its assumptions—management will not have a quantitative sense of where they are with respect to the adequacy of the overall R&D investment. The method presented in this article offers a practical and quantitative test of reasonableness, under the assumption that major disruptive discontinuities do not occur.

Stimulating future revenue growth is a major motivation behind most R&D investments; indeed, in many companies it is the dominant motive. Yet common practices do not incorporate quantitative analysis linking incremental increases or decreases in R&D spending to future revenues, even though the economic rationale for R&D investments clearly rests on assumptions about both the magnitude and timing of future income streams (*7*). While expected returns may be estimated for some specific programs, R&D planning generally does not attempt to account for the relationship between aggregate investments for new product development and the associated revenue generated years later. What is needed is a logical scheme that makes this tie.

Delayed impact of R&D

The missing dimension is a measure of revenues to be expected at some future time given a certain aggregate level of R&D spending at an earlier time.

Several authors have suggested approaches to quantification of the payoff of R&D (*8*). Patterson analyzed new-product revenue in the Hewlett-Packard Company (*9*). An electrical engineer, he drew an analogy to the performance of a linear amplifier and proposed a model that explicitly connects R&D investment to revenue. The underlying assumption is that revenue arises from products generated by R&D investment, but with an appropriate time delay. Patterson called the ratio of revenues to R&D investment the "new product revenue gain." The model is applicable to firms that realize most of their revenue from internal investments in product development, and only a minor part from products or technologies developed by other firms.

R&D planning generally fails to tie the aggregate investments for NPD to revenue generated years later.

Patterson–Hartmann Model

For simplicity, Patterson assumed that the lifetime revenue of each generation of new products was proportional to the aggregate R&D investment at the year of launch. Hartmann modified Patterson's model by more realistically distributing the product development expenditures over the years prior to launch (*10*). The resulting Patterson-Hartmann (P–H) model quantifies the R&D yield by a parameter similar to new product revenue gain, which we refer to in this article as Gain, denoted by the Greek letter omega (Ω). It is defined as the ratio of the lifetime revenue of products launched in a particular year to the total investment needed to develop those products. Gain is a useful parameter for gauging the performance of a firm over time.

A qualitative description of the P–H model and the meaning of Gain are discussed in the next few paragraphs. Readers interested in the algebraic derivation of the P–H model, which is not repeated here, are referred to an earlier publication (*10*).

Figure 1 illustrates the timing of net investment outflows (inverted) and revenue inflows for a major product line or product platform launched in a reference year labeled zero. The investment curve includes all expenses in research, technology demonstrations and product development associated with the particular product platform. The revenue stream includes income from sales, service and supplies in subsequent years derived from the subject product platform. Gain is the ratio of the total revenue divided by the total investment. In this example, $\Omega = 15$.

Normalized wave shapes for investment and revenue can be determined from the numbers plotted in Figure 1 by dividing by the respective lifetime totals. These wave shapes quantify the time lag between investment and revenue, which can be characterized by a time-to-market parameter. In the context of the model, a meaningful parameterization of time-to-market is the time interval between the investment wave peak and the revenue wave peak.

To illustrate the meaning of Gain, it is useful to imagine the value-creation chain for a hypothetical firm that develops, manufactures and markets its own products, and write a relation between the lifetime revenue from sold products and the R&D invested to develop them,

$$(\textit{Lifetime product revenue}) = (\textit{R \& D investment}) \cdot KN\,(fU + f'S)$$

where K is the number of product designs generated per R&D dollar, N is the number of product units manufactured, U is the unit manufacturing cost, S is the cost of supplies and service, and f and f' are the price-to-cost ratio for the product and supplies/service, respectively. From this expression, the Gain Ω for this hypothetical firm is,

$$\Omega = KN(fU + f'S).$$

Thus, Gain measures aspects of the innovative firm's business model, reflecting factors such as the cost and volume of units sold and the ratio of price to manufacturing cost. These in turn are reflections of market size, competitive position, effectiveness of marketing, sales, manufacturing functions, and the market-making or share-taking strength of the product offerings. Its order-of-magnitude can be readily estimated. For example, at Xerox, the average R&D expenditure for a typical product platform was $1/K$ ~ \$250M, with N ~ 100,000 units manufactured at a cost of U ~ \$8,000, and price-to-cost ratio f ~ 2.4 (see *11*). For this example, approximately $S \sim U$ and $f' \sim f$, and we estimate $\Omega \sim 15$.

The expression above is Gain for a particular product line. For R&D planning and projections of future revenue waves in a format similar to the upper panel of Figure 2, an average across all the firm's product lines is required. In principle, this "enterprise" Gain could be

"R&D Gain" is a useful parameter for gauging a firm's performance over time.

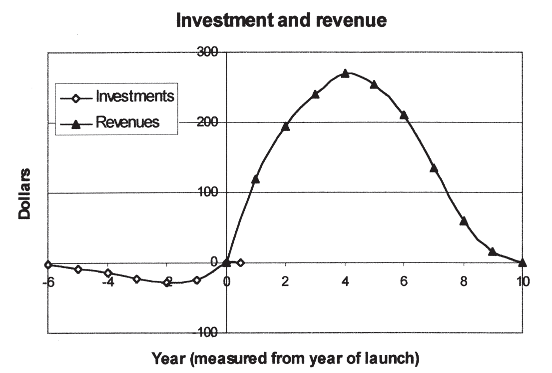

Figure 1.—Investments (inverted) and revenues are sketched for a product platform launched in year zero. The lifetime revenue divided by the lifetime investment is the Gain, here 15. The wave duration parameters are n_p = 2.6 and m_p = 4.3 years.

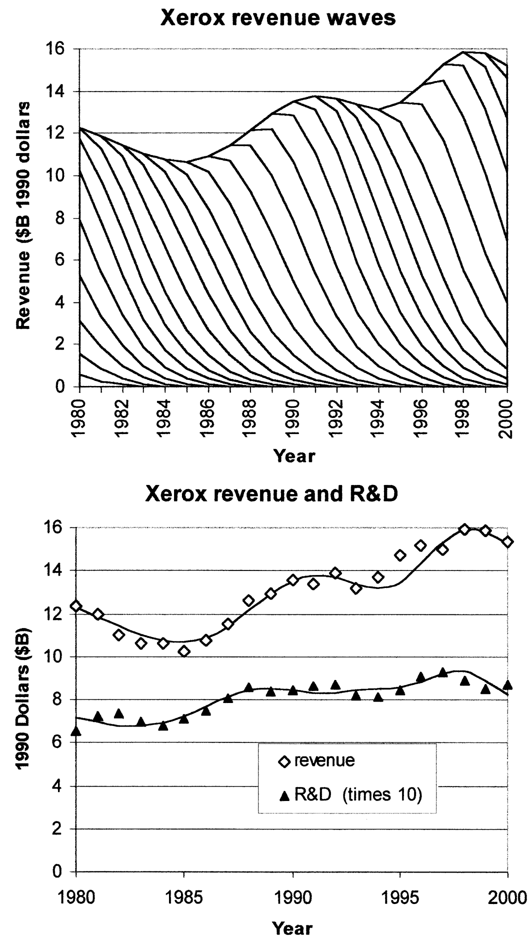

Figure 2.—The top panel illustrates decomposition of the revenue time series for Xerox into revenue waves. The bottom panel compares the historical values (plotted points) of R&D investment and revenue to the sum of the fitted waves (curves) in 1990 dollars.

built up from the Gains of individual product lines, as illustrated earlier (*10*). For a large firm, this relationship is complex and requires the evaluation of dozens of business cases, one for each of the firm's product lines. This raises the question whether Gain can be estimated another way. In the following section, we describe how the historical values of Gain at the "enterprise" level can be extracted from the firm's revenue and R&D time series.

Determining Gain from R&D and Revenue Time Series

Inputs required for estimating the Gain from the annual R&D and revenue time series are the shapes of the investment and revenue curves. These shapes can be estimated from historical revenue and investment data for specific product lines.

We have devised three methods for estimating historical Gain values. The first method, summarized in the next paragraph, applies to a simple situation where Gain and growth rate happen to be constant over time. The second and third methods, described in "Estimating Gain from Annual Revenue and R&D Time Series," next page, apply to a general situation where parameters may vary year-over-year.

Analytical relationships between Gain and the revenue growth rate can be deduced from the P–H model. A closed-form equation is not obtained, so relationships between parameters must be investigated numerically. However, a useful closed-form relationship can be derived (*10*) under the simplifying assumptions that the firm's revenue and product investment are both growing at a constant annual rate, *g*. In that case, R&D intensity, *D*, will also be constant year-over-year.

$$\Omega D = \frac{[\beta_0 + \beta_1(1+g) + \beta_2(1+g)^2 + \ldots]}{\left[\alpha_0 + \dfrac{\alpha_1}{(1+g)} + \dfrac{\alpha_2}{(1+g)^2} + \ldots\right]}$$

The symbols α_k and β_k denote the factors that quantify the revenue and investment wave shapes shown in Figure 1 (normalized so that they sum to unity). This relationship becomes simpler if the waves are hypothetically sharply spiked in years n_p before and m_p after the year of product launch,

$$\Omega D \to (1+g)^{m_p+n_p}.$$

Both relations show that if ΩD is equal to 1, the revenue growth rate will be zero. If the waves are not sharply spiked but spread out a few years before and after the respective peaks, numerical comparisons show that the simpler relation above is reasonably accurate if the wave durations are represented by $m_p = \sum i\alpha_i$ and $n_p = \sum i\beta_i$. A useful quantitative measure of time-to-market is $m_p + n_p$ years.

To summarize, for the simple case of constant growth rate, the Gain value can be estimated using average values of *D, g* and the durations of the revenue and investment waves.

Determining Gain: Examples

We estimated historical values of Gain over two decades for IBM, Xerox, Canon, and Hewlett-Packard using both the analytic and iterative methods of analysis (*12*). The revenue and R&D time series were expressed in constant 1990 dollars estimated using the Department of Commerce GDP implicit price deflator. We did this because current dollars will distort both inter-temporal and inter-firm Gain comparisons if rates of inflation vary significantly among time periods, or if the duration of revenue and spending curves differs substantially between firms.

The wave shapes were estimated for Xerox by two of the authors with extensive R&D experience there. We assumed that the parameters for IBM are similar (*13*). We assumed similar shapes for HP and Canon, except the revenue life is shorter to reflect the more rapid replacement of these companies' products, which have lower prices (*14*). The sensitivity of Gain to estimates of error in wave duration can be readily estimated (*15*). The upper panel of Figure 2 illustrates the decomposition of Xerox annual revenue into a series of revenue waves, one originating each year. The lower panel compares the sum of the waves to the historical R&D and revenue time series to illustrate the accuracy of the fit. Figure 3 plots the Gain time series determined by both methods for Xerox, IBM, Canon, and HP.

Figure 3 shows that the Xerox Gain peaked in the early 1980s and again after 1990. We interpret these peaks as the result of the highly successful "Ten-series" products launched in the early 1980s and the digital *Docutech* products launched in the early 1990s. Over the 20-year period, the overall trend is decreasing, which may reflect the commoditization of the copying and printing industry. A similar downward trend is found for Canon. For HP, the trend is upward, which we interpret as a reflection of its success in desktop printing. At IBM, Gain showed a marked decrease during the late 1980s followed by recovery during the 1990s, tracing the decline of IBM's mainframe computer business and subsequent success of IBM's new strategy under the leadership of Louis Gerstner.

Financial performance and Gain

Given the observable differences in Gain among these firms, one naturally asks whether firms with higher Gain are more profitable. An answer to this is beyond the scope of this paper, but evidence from a small number of firms is suggestive of an association between Gain and the firm's financial performance. Taking Return on

Estimating Gain from Annual Revenue and R&D Time Series

Two methods are described. One is an analytic approach that solves a set of simultaneous linear equations for the unknown Gain parameters. The other is an iterative approach, simpler to apply, that yields a close approximation to the analytic method.

Analytic Method

The analytic method solves a set of simultaneous linear equations for the product development investments and corresponding lifetime revenues. The derivation of these equations is discussed in reference (*10*). The annual R&D time series denoted E_k are expressed algebraically in terms of investment waves, whose shape is described by the factors β_i. The unknown parameters are the parameters P_k representing the total investment for products launched in the year k. For example, for the years 1980 to 2002, there are 23 linear equations of the form

$$E_{1981} = \beta_0 P_{1981} + \beta_1 P_{1982} + \beta_2 P_{1983} + \ldots$$
$$E_{1980} = \beta_0 P_{1980} + \beta_1 P_{1981} + \beta_2 P_{1982} + \ldots$$

The terms continue until β_i vanishes; our example uses a wave shape with 7 terms, β_0 to β_6. Continued until 2002, values of P_k for 2003 and later appear. These represent investment in products already under development that will launch after 2002.

In this example, there are 23 E_k parameters and (23 + 6) P_k parameters. To proceed, one must make an assumption for the extra P_k numbers. Our assumption is that for the years beginning in 2003, the values are projected from the year 2002 using a growth rate equal to the average growth rate for the preceding few years (*22*). This reduces the problem to 23 equations with 23 unknowns. In matrix notation, the equations can be written $E = BP$, where the 23-by-23 matrix B has the form,

$$\begin{array}{cccccccccccccc}
\beta_0 & \beta_1 & \beta_2 & \beta_3 & \beta_4 & \beta_5 & \beta_6 & 0 & 0 & & & & & \\
0 & \beta_0 & \beta_1 & \beta_2 & \beta_3 & \beta_4 & \beta_5 & \beta_6 & 0 & & & & & \\
0 & 0 & \beta_0 & \beta_1 & \beta_2 & \beta_3 & \beta_4 & \beta_5 & \beta_6 & \cdots & & & & \\
 & & \vdots & & & & & & & & \vdots & & & \\
 & & & & & & & & 0 & \beta_0 & \beta_1 & \beta_2 & B_3 \\
 & & & & & & & \cdots & 0 & 0 & \beta_0 & \beta_1 & B_2 \\
 & & & & & & & & 0 & 0 & 0 & \beta_0 & B_1 \\
 & & & & & & & & 0 & 0 & 0 & 0 & B_0
\end{array}$$

Here $B_N = \sum_{k=N}^{6} \beta_k (1 + g)^{k-N}$, and g is the assumed growth rate in the late years. The solution is $P = B^{-1} E$, where B^{-1} is the inverse of the matrix B.

The approach is similar for the revenue time series, except that the additional unknown parameters are before 1980, rather than after 2002. The annual revenue R_k is expressed algebraically in terms of the lifetime revenue W_k for products launched in year k, and the factors α_i for the shape of the revenue wave,

$$R_{1980} = \alpha_0 W_{1980} + \alpha_1 W_{1979} + \alpha_2 W_{1978} + \ldots$$
$$R_{1981} = \alpha_0 W_{1981} + \alpha_1 W_{1980} + \alpha_2 W_{1979} + \ldots$$

This example uses 10 terms, α_0 to α_9. Again we have to make an assumption to reduce the number of unknowns. Our assumption is that the growth rate of W_k for years before 1980 is the same as the average growth rate just after 1980. In matrix notation, the resulting 23 equations with 23 unknowns can be written as $R = AW$, where the matrix A has the form,

$$\begin{array}{cccccccccccc}
A_0 & 0 & 0 & 0 & & & & & & & & \\
A_1 & \alpha_0 & 0 & 0 & \cdots & & & & & & & \\
A_2 & \alpha_1 & \alpha_0 & 0 & & & & & & & & \\
\vdots & & & & & & & & & & & \\
A_8 & \alpha_7 & \alpha_6 & \alpha_5 & \alpha_4 & \alpha_3 & \alpha_2 & \alpha_1 & \alpha_0 & 0 & 0 & \\
A_9 & \alpha_8 & \alpha_7 & \alpha_6 & \alpha_5 & \alpha_4 & \alpha_3 & \alpha_2 & \alpha_1 & \alpha_0 & 0 & \cdots \\
0 & \alpha_9 & \alpha_8 & \alpha_7 & \alpha_6 & \alpha_5 & \alpha_4 & \alpha_3 & \alpha_2 & \alpha_1 & \alpha_0 & \\
\vdots & & & & & & & & & & &
\end{array}$$

Here $A_N = \sum_{k=N}^{9} [\alpha_k / (1 + g)^{k-N}]$, and g is the assumed growth rate in the early years. The solution is $W = A^{-1} R$, where A^{-1} in the inverse of matrix A. The solutions are the vectors (time series) P_k and W_k. The Gain time series is simply $\Omega_k = W_k/P_k$ (*23*).

Iterative Numerical Method

The second method is a numerical approach in which the magnitudes of the waves for each year are adjusted iteratively until the simulated time series closely matches the actual time series. First, the annual R&D is expressed algebraically as the sum of product development waves. We start with a trial value for the magnitude of the wave for the earliest year, and then adjust the growth rate g of the waves. Initially the trial value of g is the same for all years. Then g is adjusted up or down, year-by-year, until the simulated R&D time series closely matches the actual time series. The goodness of fit can be monitored by the sum of the squares of the difference between the simulated and the actual time series.

Similarly, the annual revenue is expressed algebraically as the sum of revenue waves. For each year, the magnitude of the revenue wave is the lifetime product investment ending that year multiplied by a trial value of Ω. To adjust the magnitude, we iteratively adjust Ω up or down, year-by-year, until the simulated revenue time series closely matches the actual time series. Again, the goodness of fit can be monitored by the sum of the squares of the difference between the simulated and the actual time series.

The two methods are essentially equivalent if the iteration is continued to reduce the residual to a negligible value. **—G.H., M. M. and R.R.**

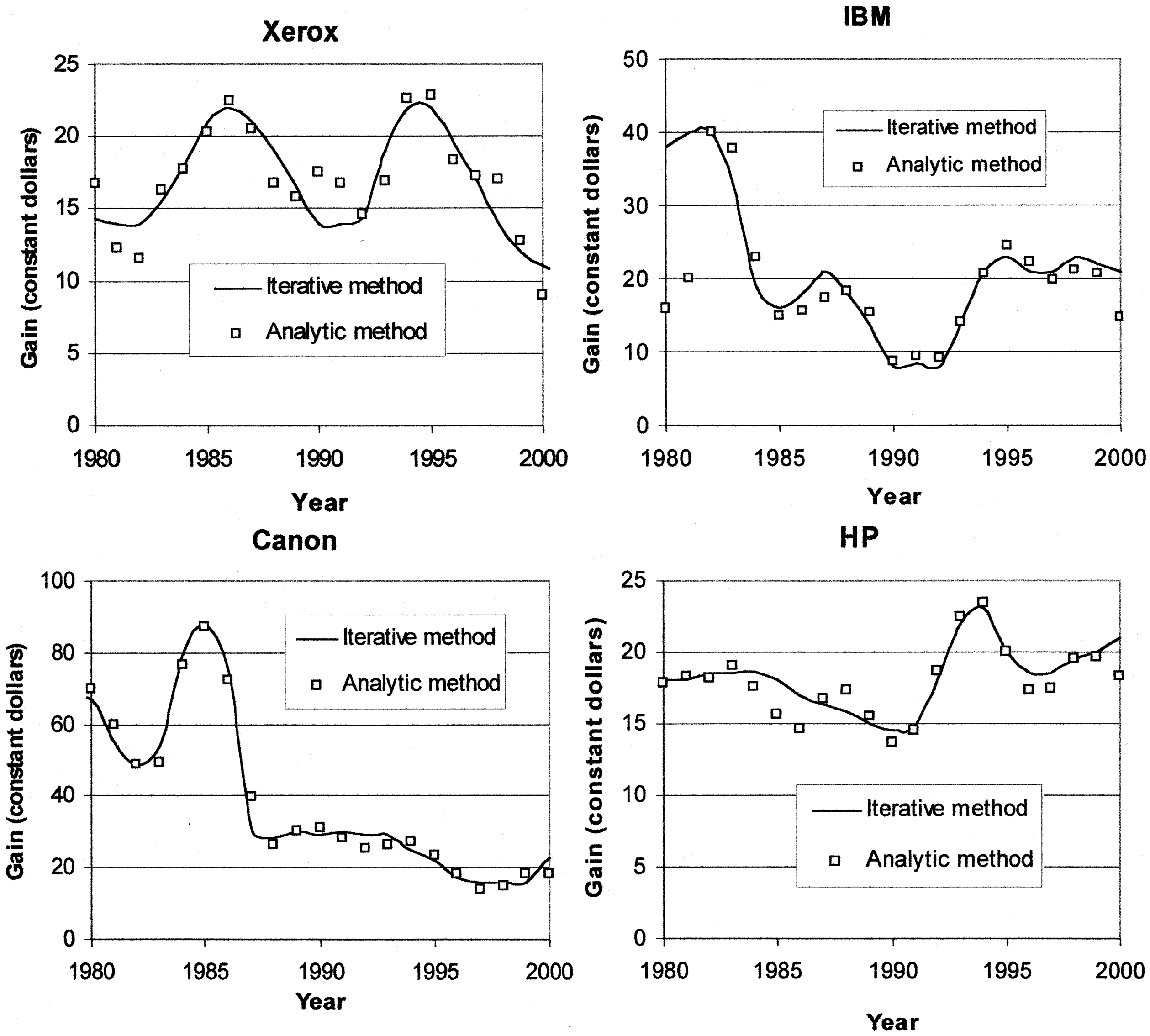

Figure 3.—Gain for Xerox, IBM, Canon, and Hewlett-Packard estimated by the analytic method (plotted points) and iterative method (curves). The wave duration parameters are assumed to be m_p = 4.3 and n_p = 2.3 (Xerox and IBM) and m_p = 2.8 and n_p = 2.3 (Canon and HP).

Assets (ROA) as a relevant measure of financial performance, we selected the largest firms (*16*) in semiconductors (Intel, Texas Instruments and AMD), in pharmaceuticals (Johnson & Johnson, Merck and Pfizer), and in computers and office products (IBM, Hewlett-Packard, Microsoft, and Xerox). The Gain time series was determined by the iterative method (*17*). The results are summarized in Table 2.

Because revenues are realized years after the underlying R&D expenditures, examination of the relationship between Gain and profitability should reflect a lag. For the ten selected firms, Figure 4 plots the relationship between Gain and ROA, each averaged over five years, with ROA four years later. A strong correlation is found, with correlation coefficient R^2 equal to 0.84. The observed relationship (*18*) is ROA% = 0.98Ω − 9.2%.

Figure 5 shows that ROA is also strongly correlated with revenue growth rate, with correlation coefficient R^2 of 0.88 for the five-year average (*19*). Because both Gain and ROA are highly correlated with the revenue growth rate, it is arguable that market growth rates, rather than R&D effectiveness, drive both Gain and ROA. Nevertheless, we believe that these relationships are at least suggestive that firms that achieve higher values of Gain will also achieve higher levels of financial performance (*20*).

Gain as a Planning Tool

An earlier section showed that past values of Gain and any trend toward larger or smaller values can be determined from historical financial data. A decrease in Gain may reflect deterioration of market size or market share, or may indicate a problem with product competitiveness. We note that Gain could also change in response to changes in time-to-market (the time interval between R&D investment and revenue collection), for example, by reduction of product development time or shortening of the product revenue stream. Technology and product managers should strive to understand which factors have caused Gain to change. They should also compare product-level Gain to enterprise-level Gain, which can differ significantly. The drag of mediocre products and canceled R&D projects gives insight into R&D productivity issues.

Competitive benchmarking

Historical Gain analysis can be performed on a firm's competitive cohort as an element of benchmarking. Competitive benchmarking may already have disclosed similarities (or differences) in R&D intensities. The main uncertainty involved in extending the comparison to Gain arises in regard to estimates of competitive firms' investment and revenue wave shapes. When benchmarking discloses significant variations in Gain among comparable firms, as for example Xerox, Canon and HP, management will be alerted to explore which factors cause the observed differences.

Planning for growth

Barring unpredictable events, Gain analysis can provide a test of the reasonableness of the R&D budget by identifying the level of R&D required that is consistent with the revenue growth aspirations of the firm. This idea is illustrated for a hypothetical firm using the planning chart shown in Figure 6. The curves in the chart represent combinations of Ω and D that yield specified revenue growth rates—in this case 0%, 5%, 10%, and 15%, computed using the equation that relates ΩD and growth rate. The current state of the hypothetical firm is also indicated on Figure 6, with R&D intensity of 5.5%, Gain of 32 and revenue growth rate of 10 percent.

Firms that achieve higher levels of Gain are likely to achieve higher levels of financial performance.

If, for example, management desires the firm to grow at an annual rate of, say, 15%, either or both the Gain or R&D intensity must be increased so that the plotted point lies on the 15% growth curve. The value of the Gain Δt years in the near future can be projected from the current value of Gain $\Omega(t)$, its trend $d\Omega/dt$ toward a larger or smaller value, and possible plans to change the Gain value by an amount $\Delta\Omega$ from investments or anticipated changes in marketing, sales and so on.

We then use the projected Gain value, $\Omega(t+\Delta t)=\Omega(t)+\Delta t d\Omega/dt+\Delta\Omega$, to determine the required value of R&D intensity, D. The points labeled **a, b** and **c** mark three of many possible hypothetical combinations of Ω and D that will achieve the targeted 15% growth rate. Case **a** illustrates a situation where management decides to invest to increase both Ω and D, raising the possibility of making tradeoffs between investments in product development and market development. Case **b** illustrates how much D must be increased to achieve the desired growth rate when Ω is anticipated to be constant. Case **c** illustrates how large an increase in D would be required to offset an anticipated decline in Ω.

This approach to setting the aggregate R&D budget offers a route to better understanding the range of required values for R&D spending that will satisfy the strategic revenue growth objectives of the firm. For revenue growth, the P–H model requires that the Gain value be somewhat greater than the inverse of its R&D

Table 2.—Patterson-Hartmann Model Parameters and Financial Performance for 10 Firms

	Five-year average values		Ten-year average values		
Firm	Gain Ω 1991–1995	ROA (%) 1995–1999	R&D intensty (%) 1991–2000	ΩD product 1991–2000	Wave shape parameters (years) n_p, m_p
AMD	10.0	0.7	17.9	1.8	2.7, 2.8
Intel	29.0	22.7	10.2	2.7	2.7, 2.8
TI	21.1	6.3	10.4	1.8	2.7, 2.8
HP	19.5	9.7	7.5	1.4	2.3, 2.8
Xerox	18.2	4.2	5.9	1.0	2.3, 4.3
J&J	23.5	14.6	9.3	2.1	2.7, 5.5
Merck	28.0	16.9	8.1	2.7	2.7, 5.5
Pfizer	18.0	14.0	13.8	2.4	2.7, 5.5
IBM	14.9	7.2	5.9	1.1	2.3, 4.3
Microsoft	35.6	25.5	14.2	4.0	1.7, 2.8

intensity. The revenue growth rate will be zero if $\Omega = 1/D$. This is the condition where R&D generates just enough new products (and new revenue waves) to keep the total annual revenue flat, while older products with declining revenues contribute less. Every CEO should be aware of the values of the parameters for his or her firm that defines this zero-growth condition.

Setting aggregate R&D level by DCF or real options analysis

The economic evaluation of proposed investments in R&D for development of new product platforms can be accomplished, in principle, by discounting expected future cash flows (DCF) or by real options analysis. The practical application of these techniques, however, is limited in two respects. First, for analysis of individual investments, it is difficult to handle the uncertainty that characterizes all R&D investments. Second, in assessing the aggregate R&D budget for dozens of product development programs, the information processing requirements of these methods can make their application prohibitive.

With respect to individual programs, a high degree of uncertainty prevails in the early stages of speculative new technologies. Analysts may attempt to reflect this uncertainty by applying very high discount rates, effectively biasing the analysis against the most novel opportunities. After the uncertainty is largely resolved, DCF becomes a valid tool for investment decisions. But by that point much of the investment already may have been committed. Real options analysis provides an alternative framework for understanding the uncertainties inherent in early-stage product development before committing large amounts of money. The best-known example of applying real options at the enterprise level is Merck, where it was applied for drug development under the leadership of CFO Judy Lewent (*21*).

For a large corporation, it may be impractical to build up a full portfolio of analyses of individual product programs to assess the payoff from the total R&D expenditure. For example, for a firm the size of Xerox, this would require analyzing scores of product programs whose status is continuously changing. The advantage of using Gain for budget planning is that it can be done in a single undertaking using readily accessible data. In addition, simulations of revenue can be done for a variety of "what-if" planning cases and provide additional insights to the planning process.

Summing Up

Top managers in technology-based companies must strive to strike a balance between the level of R&D investment and competing expenditures. At least four types of logic come into play at various points in the routine practices for R&D budget-setting in such companies, as observed at Xerox, IBM and Lucent. These involve corporate financial boundaries, competitive benchmarking, product portfolio analysis, and the pursuit of speculative research opportunities.

Even when taken together, this logic provides insufficient guidance for setting the aggregate level of R&D spending. The missing dimension is a measure of the yield as expressed by the Gain parameter in the P–H model. The P–H model relates the revenue growth rate to the Gain parameter, R&D intensity, and durations of product development and revenue waves. Through investment decisions and operating policies, top managers influence all four of these factors. For example, management can strive to accelerate the growth

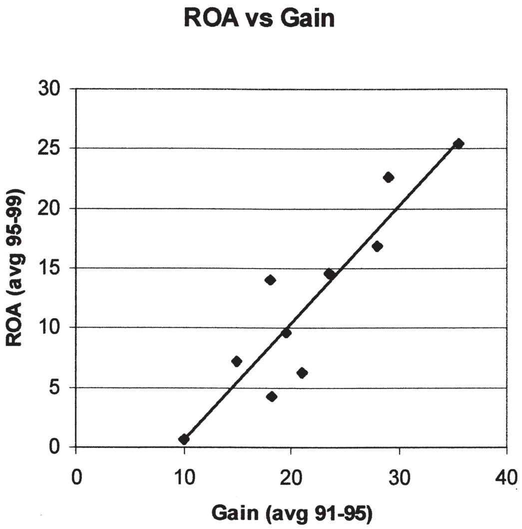

Figure 4.—Correlation of ROA and Gain for 10 R&D-intensive firms.

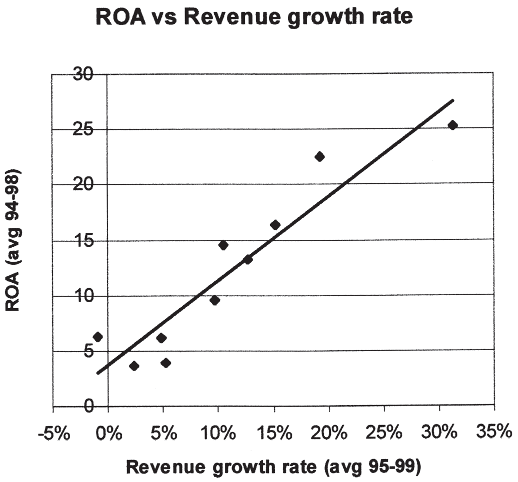

Figure 5.—Correlation of ROA and revenue growth rate for 10 R&D-intensive firms.

rate by decreasing product development time, or by allocating R&D spending to emphasize products with shorter revenue life cycles.

We have shown that Gain can be employed as a tool for determining the size of the aggregate R&D budget required to meet the growth aspirations of the firm. The P–H model shows that the product of Gain and R&D intensity determines revenue growth rate. The planning approach outlined here will enable managers to explore more fully the growth implications of various combinations of these two key parameters.

We also suggest that R&D benchmarking can be more informative if expanded to include estimates of the value and trend of Gain for competitive firms. The P–H framework provides a method to discuss estimates of the expected future revenue growth rates. Of course, in some situations benchmarking applications may be limited by the difficulty of obtaining reliable data defining the shapes of product investment and product revenue waves. A further complication arises if the shapes have shifted over time, but if these changes are known, they can readily be incorporated into the P–H model analysis.

In summary, the framework of analysis we propose for determining the aggregate R&D level has three elements. First is the determination of both current and historical values for Gain using either of two new methods presented here for the first time. From this, the analyst can identify trends, if any, over time. Where variations exist, it may be valuable to identify organizational or external factors that might explain them. The second element involves competitive comparisons; historical values of R&D intensity, Gain, and growth rates for the firm should be benchmarked against comparable measures for the firm's competitive cohort, supplemented by analysis intended to explore factors accounting for the differences observed. The third element turns from history to the future, assessing the adequacy of planned R&D expenditures given the Gain, to achieve a desired revenue growth rate. ⊙

R&D benchmarking could be more informative if it included estimates of the value and trend of Gain for competitors.

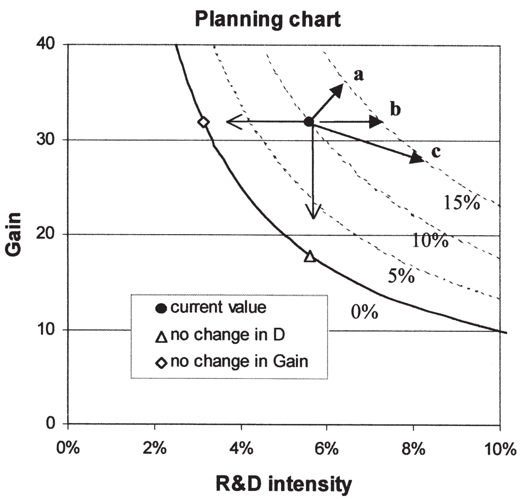

*Figure 6.—Current values of Gain and R&D intensity for a hypothetical firm are represented on this planning chart by the solid symbol, which lies on the 10 percent growth rate curve (computed with $m_p + n_p = 6$). Points **a, b** and **c** illustrate combinations of Gain and R&D intensity that achieve the targeted growth rate of 15 percent.*

Acknowledgements

The authors wish to acknowledge helpful conversations with Paul Horn of IBM and Robert L. Martin of Lucent. We also thank our colleague Rafik Loutfy, McMaster University, formerly of Xerox, for insightful conversations on this subject.

References and Notes

1. See, for example, G. K. Morbey, R&D: Its Relationship to Company Performance, *J. Product Innovation Management,* 5, pp. 191–200, 1988; G. K. Morbey and R. N. Rethner, How R&D Affects Sales Growth, Productivity and Profitability, *Research-Technology Management,* 33 (3), pp. 11–14, 1990, who report a significant correlation between R&D intensity and subsequent revenue growth, using a database of 727 companies, as well as a positive correlation between profit margins and R&D expenditure per employee. R. Henderson, I. Cockburn, Scale, Scope and Spillovers: the Determinants of Research Productivity in Drug Discovery, *RAND Journal of Economics,* 27, pp. 32–59, 1996, report on a study of patent data for pharmaceutical firms, which found that size enables an advantage due to shared knowledge and infrastructure. They noted that competitive advantage correlates with the absolute amount of R&D, rather than R&D intensity. B. Lev, *Intangibles Management, Measurement, and Reporting,* Washington D.C., Brookings Institution Press, 2001, cites evidence (pp. 53–58) that investors believe that R&D investment enhances the firm's value, and that investors discern the contribution of R&D across industries, firm sizes, and stages of maturity. P. Boer, Linking R&D to Growth and Shareholder Value, *Research-Technology Management,* 37 (3), pp. 16–22, 1994, examines how increases in earnings growth can be realized from R&D investments.

B. Hall, The Stock Market's Valuation of R&D Investment During the 1980's, *AEA Papers and Proceedings,* 83, pp. 259–264, 1993, introduces the idea that a firm's value depends on various forms of capital, including the intangible value of sustained R&D investment. In later work, B. Hall, Innovation and Market Value, in Ray Barrell, Geoffrey Mason and Mary O'Mahoney (eds.), *Productivity, Innovation and Economic Performance,* Cambridge, Cambridge University Press, 2000, analyzes the relationship between market value and innovation, and shows that financial markets value R&D.

2. J. Armstrong. It's Possible To Spend Too Much on RD&E. *Research-Technology Management,* 40 (5), pp. 10–11, Sept.–Oct. 1997.

3. K. Hansen, M. Weiss and S. Kwak. Allocating the R&D Resources: A Quantitative Aid to Management Insight. *Research-Technology Management,* 42, (4) pp. 44–50, July–Aug., 1999, describe a hierarchy of three decision levels to determine the R&D budget. Their study focuses on the second level.

4. R. G. Cooper, S. J. Edgett and E. J. Kleinschmidt, Portfolio Management for New Products, pp. 16–35, Portfolio Study, McMaster University, Hamilton, Ontario, Canada, 1997, have described portfolio management for new product development. G. Mitchell and W. Hamilton, Managing R&D as a Strategic Option, *Research-Technology Management,* 27 (3), pp. 15–22, May–June 1988, and also R. Gunther McGrath and I. C. MacMillan, Assessing Technology Projects Using Real Options Reasoning, *Research-Technology Management,* 43 (4), pp. 35–49, July–Aug. 2000, have addressed the management of uncertainty in each phase of R&D, and discussed how to use real options reasoning to guide investment decisions with high uncertainty. G. C. Hartmann, and M. B. Myers, Technical Risk, Product Specifications, and Market Risk, in *Taking Technical Risks,* Lewis M. Branscomb and Philip E. Auerswald (eds.), Cambridge: MIT Press. pp. 30–43, 2001, have examined the interplay of product development risk, market risk and investment amount.

5. R. S. Rosenbloom and W. J. Spencer, (eds.), *Engines of Innovation,* Boston: Harvard Business School Press, 1995, have argued that this rationale is no longer valid.

6. Interviews were held by Mark B. Meyers in 2000 with Paul Horn, Sr. Vice President for Research and staff at IBM Watson Research Center, Yorktown Heights, New York and Robert L. Martin, CTO, at the Bell Laboratories, Murray Hill, New Jersey.

7. If carried out systematically, the product portfolio approach can provide estimates of the return to be expected from the R&D investment. But product portfolio planners usually do not develop a future revenue scenario for each future product, and do not aggregate them across the firm and over time. Consequently there is no systematic information on how future revenues will change, including the impacts of declining revenues from legacy products.

8. See, for example, the review by J. R. Hauser and F. Zettelmeyer, Metrics to Evaluate RD&E, *Research-Technology Management,* 40 (4), pp. 32–38, 1997, of various metrics in use.

9. M. Patterson. Linking Product Innovation to Business Growth, *J. Product Innovation Management,* 15, pp. 390–402, 1998.

10. G. C. Hartmann. Linking R&D Spending to Revenue Growth, *Research-Technology Management,* 46 (1), pp. 39–46, 2003.

11. G. C. Hartmann. Performance Trends for Marking Technologies in Copiers and Printers. *Journal of Imaging Science and Technology,* 44 (3), pp. 204–209, May/June (2000).

12. The sources for historical revenue and R&D information are Standard and Poor's Compustat and company annual reports. R&D excludes market research, customer or government sponsored research and development, and routine ongoing engineering expenses to maintain or improve existing product lines. Minor acquisitions were treated as business as usual, except for HP, where revenue and R&D associated with Agilent's spin-off in June 2000 is excluded from 1996 to 2000. Xerox revenue and R&D expenses for 1997–2000 were taken from the 2001 annual report.

13. The time required for product development depends on product complexity, often measured using metrics such as the number of drawings, parts and lines of computer code. Products from Xerox and IBM have similar levels of complexity; hence, for purposes of illustration we assumed the product development times for both companies were similar. The duration of the revenue stream from a product line depends on how often it is replaced in the market by a new generation of products, which in turn depends on factors including initial product price and rate of technological progress. Our assumption is that in the main, products from these two companies had a similar spectrum of price, supplies and service. Consequently, for the purpose of our example, we have assumed a similar duration of the revenue waves.

14. M. Patterson, (ibid), illustrates normalized revenue wave data for HP in Fig. 3, from which we estimate $m_p = 2.8$ years.

15. The sensitivity of the Gain estimate to the wave shape assumptions can be estimated. For example, assuming 4% average growth rate, the Gain changes by about 4% when the parameter $m_p + n_p$ changes by one year.

16. The firms were the largest (by annual revenues) on the 2002 list of the *Fortune* 500, except for computers, where Dell was omitted because it is not a significant performer of R&D. Revenue and expenditure amounts were restated as constant dollars, for reasons previously discussed.

17. The revenue and R&D time series from 1980 to 2000 was acquired from public sources and expressed in 1990 constant dollars. Acquisitions or divestitures were treated as business as usual, except for Pfizer where the financial impact was large. Unconsolidated revenue and R&D prior to the merger in 2000 with Warner Lambert is available in Pfizer annual reports up to and including 1999.

The product development cycle was modeled by waves with short, medium and long durations (Table 2). Long product development times were assumed for semiconductor and pharmaceutical/health care firms, reasoning that long times are required for development of major product platforms and major manufacturing capabilities. Following the same logic, medium product development times were assumed for office product firms, and medium and short development times were assumed for firms offering computer products.

The product revenue stream was modeled by waves with short, intermediate and long duration (Table 2). For pharmaceutical/health care firms, a long revenue wave was assumed, recognizing that products from these firms often generate revenue for a decade or more. Intermediate-duration revenue waves for revenue streams lasting about 5 years were assumed for IBM and Xerox, which develop complex equipment. The shortest revenue wave was assumed for firms that supply desktop products frequently replaced by customers, and for semiconductor firms, which frequently upgrade the performance of their processors.

18. The correlation is robust across lags of 3–5 years. A similar strong relation was found when the running average time was reduced to 3 years.

19. ROA is proportional to revenue growth rate according to the sustainable growth rate equation, with coefficient (equity/assets)(profits after tax)/(Δ retained profits). From financial data during the mid-'90s, the average value for the ten firms of the coefficient is 1.1, within 10% of the value from the correlation, suggesting that as a group, the firms were near their sustainable growth rates.

20. The key uncertainties inherent in this analysis are our assumptions about the shapes of the investment and revenue waves for all but two of the firms. What is needed is a Gain estimate independent of these shapes for the major product platforms of each firm. One approach would be to compute the Gain directly from data on product price, cost, and quantity sold.

21. N. A. Nichols. Scientific Management at Merck: An Interview with CFO Judy Lewent. *Harvard Business Review,* pp. 89–99, Jan.–Feb. 1994.

22. Because the method involves a simultaneous fit of the parameters to the data, in principle the values of all parameters for all years are affected each time a new year is added to the series. However, if the data for the newest year are close to the projections used in the previous computation, the effect on values for earlier years is small.

23. The analytic method is numerically unstable if the curvature in the investment or revenue time series is smaller than the curvature in the respective wave shapes. Short-term fluctuations in the yearly investment or revenue may occur for reasons unrelated to the assumptions of the model, and if this happens, the model cannot follow them. The instability occurs because the method forces an exact fit to the input time series, which sometimes can only be achieved if the fitted numbers alternate in sign and grow steadily larger. This can be mitigated by smoothing the input time series. We smoothed the data using, $\overline{X}_k = (aX_{k-1} + bX_k + aX_{k+1})/(2a + b)$, with b/a equal to 1, 2 or 3, depending on the curvature. The resulting Gain time series was smoothed in the same way.