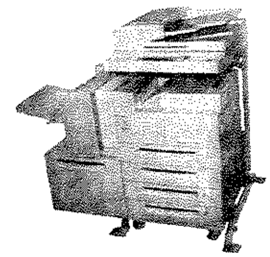
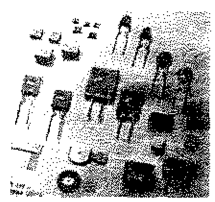
1 Journeys in Product Development

The **Xerox Corporation's** document systems have multiple systems using hundreds of parts. The design teams number in the dozens, and a project takes years.



The Microsoft Corporation's software products have dozens of feature elements, design teams number in the dozen of members, and a project takes months.

The Raychem Corporation's products have dozens of constitutive raw materials, research and development teams number in the dozens of members, and a project can take decades.



The Ford Motor Company's cars and truck have 20 systems, 166 subsystems, numerous sub-subsystems and thousands of components. There are hundreds of orchestrated design teams that number in the hundreds and a vehicle project takes years.

The design of new products is the key battleground that all companies must master to remain in business—to compete at a basic level. Product designers are the front-line troops who lead and execute the battle. Product design is a set of activities that involves more than engineering. It is fraught with risks and opportunities, and it requires effective judgment over technology, the market, and time. Studying some recent business decisions gives insight to these ideas:

- To avoid losing market share in the 1990s, commercial airplane manufacturers offered contracts to deliver aircraft at prices that were below the current development and production cost (*Wall Street Journal*, 24 April 1995). The companies were betting that they could remain profitable through improvement of their products and development processes.
- In 1985, John Akers, CEO of IBM, was considering eliminating IBM's research laboratory, a popular decision for American CEOs at the time. Instead, the lab director proposed a vision of working to develop a 1 Gbit per square inch storage medium, a vision supposedly proven physically impossible. The lab restructured around this vision and, by 1989, had developed breakthrough technology in thin-film inductive heads. The lab stayed focused on developing ever-increasing storage media, and, into the next decade, IBM maintained a 6–12-month technology lead over its competitors (Tristram 1998).
- In the 1990s, Dell Computer Corporation developed the end-to-end use of digital networks to run their corporation. With information-system intensive marketing, development, and production, Dell made it possible to completely eliminate middlemen in a low-margin industry. They connected directly to the customers via their purchasing Web site, through phone orders, and through its program of offering customized products and services. This "direct customer contact" philosophy enabled them to watch how their customers purchased and rapidly focused on desired features in new product designs. By 1999, such investment in their product delivery process made Dell the #1 computer supplier (*Wall Street Journal*, 10 May 1999).
- In 1996, both Ford and Toyota launched new family sedans. Three years earlier, each had criticized the other's model. Ford decided to increase the options in its Taurus, matching Toyota's earlier Camry, while Toyota decided to decrease the options in its Camry, matching Ford's earlier Taurus (*Business Week*, 24 July 1995). Neither really knew where the market was going or what to do.

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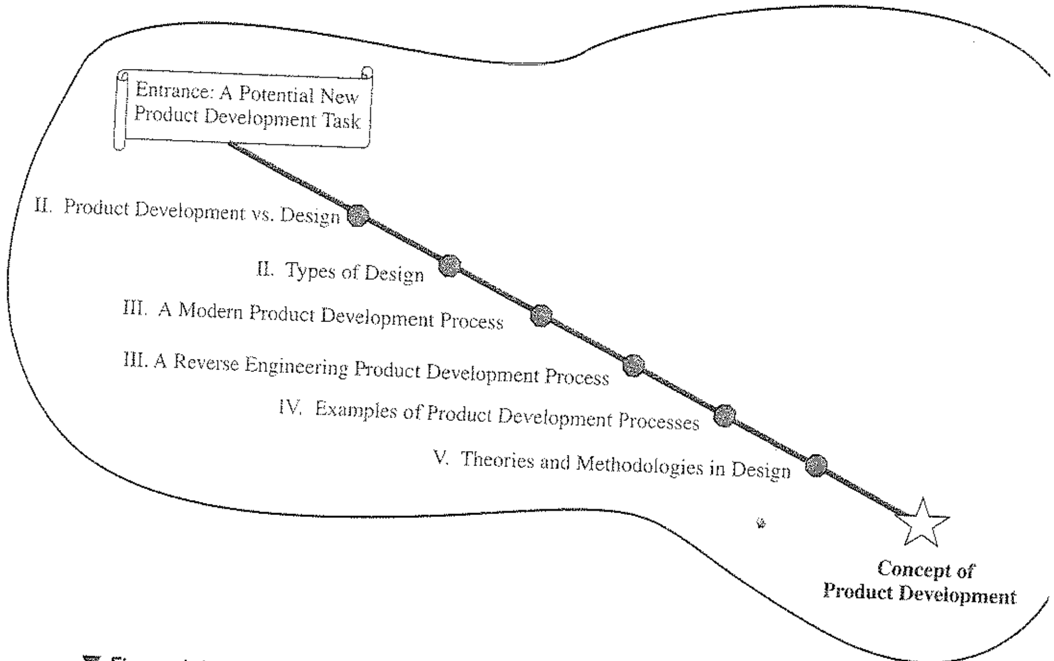
To avoid pitfalls, today's design engineers must understand and use many tools of modern product development practice. For almost all products, it is no longer acceptable to develop major enhancements without first consulting customers to forecast the market acceptance of the improvements: The risk is too high to just accept one product manager's belief in their "feel" for the market. Rather, a team must apply statistically sound measurement methods of a product's intended customer population. It is equally important to functionally architect what is required to meet the customer demands, applying rigorous methods for incorporating the best technologies. It is critically important to understand the competition and the time trends of new technology introduction into the market. It is also important to design robust performance into a product, so that the product is as high quality as possible given the price. These goals and associated methods have become the competitive weapons that allow design teams to ensure that their company leads the market. Engineers who wish to harness their drive for success need to understand product development and the application of product development tools and methods. In this book, we develop the underlying theory, methods, and practices to extract an understanding of modern product development.

I. CHAPTER ROADMAP

In this chapter, we first present a general discussion on product development and design. We then offer our view on the advancement of systematic design and a hypothesis on the evolution of design as a practice. We then examine the product development practices of a few representative companies and compare this examination with our philosophies. Finally, we discuss different theories of design that have been developed over time. Figure 1.1 shows the roadmap through the topics of this chapter.

II. AN INTRODUCTION TO PRODUCT DESIGN

By using this book, the reader will learn and practice contemporary theories of effective product design through the adaptive and/or original redesign of consumer products. Engineering design can be challenging and exciting, or it can be taxing, difficult, and unproductive. The objective here is to outline a methodology that highlights the



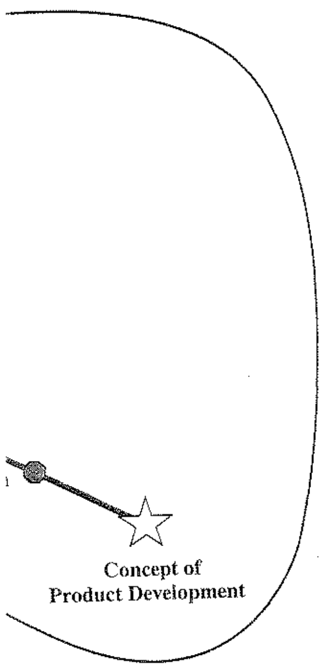
▼ ***Figure 1.1.***
Roadmap of Chapter 1.

exciting challenges of product design and allows the development team to focus on the development of a creative, effective, and profitable solution.

Thoughts for the Reader and Student of Product Design

The particular methodologies explored in this book are selected because they have the potential to satisfy three objectives of engineering design:

- to stimulate creative and inventive solutions to problems
- to ensure consideration of each of the elements necessary for successful design
- to ensure that all consequences of the application of the designed device or process throughout its lifetime are examined



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The assignments distributed in design courses are quite different than the relatively well-defined analytical problems delivered in other engineering studies. Because there is a lot less information to start with, we are called on to use our own judgment and make many, many assumptions. Most importantly, there will never be just one right answer.

Assignments of this sort, those that may not be clearly stated and are without a well-defined path to a solution, are, however, much more like those encountered in the "real world" of industry. They are distinct and more challenging than the typical end-of-chapter homework problems. Although the engineering design methodologies presented in this book are, of necessity, more formalized and detailed, there are parallels between them and the problem solution methodologies used in other endeavors. They build on, extend, and strengthen many of the procedures we use in analysis work and courses. Yet, they allow us to move from analysis to the more-complex and much-less-bounded problem of synthesis—design.

The problems encountered in product design are also amenable to many solutions. There will always be more than one way to proceed, and there will certainly never be just one "correct" solution or design. We also can't assume that we have the best answer just because we have *an* answer that appears feasible.

The problem statements we encounter require a good deal more time and effort to understand. We will most likely have to resolve conflicts between the stated functional requirements and external constraints in each of the assignments we are given. We must plan on spending a good deal more time setting up the problem than on comparable analysis tasks. We must also remember that there is a clear progression of material throughout the book. It is cumulative, so we must keep our eyes open!

Product Development Versus Design

A *product development process* is the entire set of activities required to bring a new concept to a state of market readiness. This set includes everything from the initial inspiring new product vision, to business case analysis activities, marketing efforts, technical engineering design activities, development of manufacturing plans, and the validation of the product design to conform to these plans. Often it even includes development of the distribution channels for strategically marketing and introducing the new product.

A *design process* is the set of *technical* activities within a product development process that work to meet the marketing and business case vision. This set includes refinement of the product vision into technical specifications, new concept development, and embodiment engineering of the new product. It does not necessarily include all of the business and financial management activities of product development nor the extensive marketing and distribution development activities.

Neither the product development process nor the design process encompasses the subsequent *manufacturing process,* when the products are physically made. The design of the manufacturing process, however, is generally considered part of the product development process. Often the product design process and the design of its manufacturing system must be carried out simultaneously. Effectively performing this integration is part of the study of *concurrent engineering* (Clausing 1997).

Similar to the manufacturing process that follows the product development process, there are also front-end activities that are required before product design and, based on industry, may or may not be considered part of the product development process. The *Research and Development* (R&D) phase of new product development is when new technology is developed for subsequent incorporation into products. Today, large companies in many industries try to separate the R&D process from the product development process. That is, ideally, R&D efforts create new technology and develop it to the point where the technology is encapsulated into a new system ready for immediate adoption by the product development teams, similar to out-sourced subsystems. Product development then becomes a very rapid process of tailoring technologies into new systems that meet changing market needs. Product development does not get bogged down into researching how to obtain new technology that does not really perform what is required. This paradigm will not work in all industries, but it is effective for many mechanical system industries.

Generally, such R&D to product development transfer is not perfect: the technology passed off to the product development teams may not function well in the new product concept. This mismatch can occur for a variety of reasons. Some causes are social, such as the different cultures between R&D corporate research and product development business units. Other causes include general uncertainty, such as the ability of new technology to be used in ways not foreseen by the R&D group during their development efforts. Often, though, miscommunication of specifications and form is a prime source of error; people understand the same words and descriptions differently.

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The entire set of preliminary product development activities that happen before a product is given the go-ahead for development is sometimes called the *fuzzy front-end.* This set includes the decisions on what products to consider for development. Factors include corporate strategy or the determination of what technologies and markets that a company should compete in. Business alliances can therefore impact the decisions as well as forecasted customer markets and business trends. The fuzzy front-end also includes development decisions on what the underlying portfolio architecture should be for a set of products that may be offered by a company. Design engineers play a large contributing role on the teams making these front-end decisions.

The point of this discussion is not to find a classification scheme for development activities that fits all companies and development enterprises; such a classification will always vary by industry and company. Rather, one should be aware of how a design process fits within a product development process of any company and how a product development process fits within a company's business environment.

Types of Design and Redesign

Design tasks may be classified in several different ways. To indicate the extent of the effort required, one approach is to classify a development project as *original design, adaptive design,* or *variant design.* Table 1.1 lists examples of these different types of design for various technologies.

Original design (or *inventing*) involves elaborating original (new/novel) solutions for a given task. The result of original design is

TABLE 1.1. EXAMPLES OF TYPES OF DESIGN

	Original design	Adaptive design	Variant design
Brakes	Anti-lock brakes	Brake system for a new vehicle	Resized system for a slightly changed vehicle; varying disk diameter or friction material
Steering	Assistive technology for people with disabilities (joystick, foot control)	New column including secondary functions	Resized steering column for resized chassis
Entertainment	CD media	DVD media	Laser disk media
Computing	Microprocessor	Intel 8080 chip	Pentium to Pentium II refinement in chip
Vehicles	Benz's first automobile	Unibody construction (vs. body on frame)	Any new year's model compared to older year
Bearings	Da Vinci's Self-Centering Ball Bearing	First Teflon-coated plain bearings	Different sizes in a family of related bearings

an *invention.* The invention of the transistor, the laser xerography process, and the windowed computer system complete with pointing mouse—these were all original designs. Few successful original designs occur over time, and when they do, they can disrupt the market. Consumers see the new technology, want it (either immediately or eventually), and have to replace not only the old equipment, but also the infrastructure around the old equipment. Automobiles require paved roads, gasoline, repair stations, and insurance; they do not require hay and barns. Computers on the Internet require a microprocessor and memory, a network connection, and a Web browser; they do not require operating systems or application software. Original inventions are often high-risk opportunities for changing a marketplace and then dominating it. Few companies have industrial or engineering designers that manage or are permitted to invent an entirely novel design; even fewer companies exist that can steer such an invention into market domination.

Adaptive design (or *synthesis*) involves adapting a known system to a changed task or evolving a significant subsystem of a current product (such as antilock brakes). Adaptive designs can be very novel, but they do not require a massive restructuring of the system within which the product operates. This type of design dominates the vast majority of design activities. This domination is not due to a mental laziness on the designers' part but is simply a reflection of the demands of the marketplace. Customers generally want new products that fit in their current life-style. Within the boundaries of this life-style, they evolve their system of using the product. Meeting these evolving needs and boundaries can be very profitable with reasonable risk.

Variant design (or *modification*) involves varying the parameters (size, geometry, material properties, control parameters, etc.) of certain aspects of a product to develop a new and more robust design. This type of design usually focuses on modifying the performance of a subsystem without changing its configuration. It is also implemented when creating scaled product variants for a product line. For example, a plain bearing resized to a larger load rating will require a greater surface area, and so a new larger bearing must be developed with a variant design process. Likewise, a standard restaurant-sized food processor may be reduced in power parameters, size of serving bowl, and cutting tool dimensions to create a variant for use by small households.

Redesign is a term that we use to mean *any* one of the above. Redesign does not mean variant design. Rather, redesign only implies that a product already exists that is perceived to fall short in some criteria, and a new solution is needed. The new solution can be developed through any of the above approaches. In fact, it is often difficult to argue against the maxim that "all design is redesign."

What is Engineering Design?

Another way to classify design processes is to consider the discipline within which the process operates. There are many disciplines of design, including mechanical engineering design, electrical engineering design, architectural design, industrial design, food science design, furniture design, materials design, aerospace design, and bridge/roadway design. Name any product, and there will be a design process used in its development. For this disciplinary classification, the question arises over which disciplines would benefit from systematic techniques for product development (the subject of this book). At a high level, they all would benefit, but only certain disciplines will realize the full potential of some of the methods. One approach for investigating this issue further is to explore the modeling detail used in each of the disciplines.

This book applies a model-centric and systems approach to design; it is appropriate for design processes that require and benefit from extensive modeling. A systematic effort, and the contents of this book, is devoted to exploring the activities of a design process: isolating each activity, understanding what is required as input, what is produced as output, and then establishing methods to repeatedly complete the activity. This approach is very appropriate for engineering-design activities, especially in the real-world corporate design environment. It permits many engineers to work in concert and to hand off their results to the team members working on the next or parallel activity. A model-centric approach minimizes the disruptions, explanations, and fixes (engineering changes) of this large development process. Short of removing disruptions, it also permits understanding what must be communicated among activities.

The tasks to be completed for each activity in engineering design are complicated. They require assurance of complex criteria, such as material failure due to stresses, vibrations, thermal characteristics, and dynamic analysis. For example, consider the design of an automotive vehicle. Dynamic analysis of vibration loads is required to distribute mass over the frame, select frame elements, and design joints. These considerations are critical so that the vehicle frame transmits minimal noise to the occupants, is structurally sound, absorbs impacts during a crash, and minimizes cost. Such analysis may be very complex and resource intensive, yet the success and quality of a contemporary product cannot be assured without this analysis of mechanical effects. If mechanical performance issues were not resolved with suitable modeling and analysis, many years of both failures *and* successes would be experienced without any guarantee of future performance. This trial-and-error, or Edisonian, approach would not be acceptable or lucrative. Rather, models of mechanical effects are simply required as part of mechanical product design, and, thus, the methods explored in this book are both applicable and exciting.

On the other hand, as a counterexample, consider the design of furniture. Here, failure analysis is not difficult to visualize or estimate; the craftsman easily understands required material thickness and joint construction without completing rigorous calculations or repeated experimental trials. To support a load, skilled furniture builders empirically understand what material thickness dimensions will fail and what dimensions will work just fine, and it does not take many experiences to develop this understanding. Within this intuitive context, the furniture builders must also design for appearance, fit, and feel; these issues are the crux of furniture design. This "artistic" focus is typically executed with very few customer interviews, no functional models, and no equations of performance. The advanced analytic and systematic methods in this book would be difficult to apply in detail for such furniture design tasks, although the underlying design principles remain the same.

The difference between these two design processes, mechanical systems and furniture concepts, is the level of engineering required to complete the design task. The vehicle design is an engineered product; it requires modeling to attempt the design task, certainly in any reasonably quick, accurate, and cost-effective fashion. *Engineering design* is thus a process that requires modeling to complete the design task. The furniture design problem, on the other hand, is one of *craftsmanship*. Here, one need only estimate effects intuitively, create a mental image or drawing of the concept, and then build the piece. Applying the craftsmanship approach to engineering design tasks is often attempted, but it rarely produces reliable or quality devices for the consumer.

Given this contrast, what constitutes an effective approach when we are confronted with a new design task? We explore this question further in this chapter. To do this, we present a modern product development process for engineered products. Then we show and briefly explain how this approach is applied, or has been applied, at various companies. This discussion provides necessary perspective on differences in product development processes. It also demonstrates the essential qualities that may be derived from a well-developed

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approach to product design. Satisfying and safe products are not created accidentally.

Context: The Light Side

Product design is much more than a blind search for a successful creation. It is founded on principles we must learn and repeat.

A story (author unknown) provides a further refinement of this idea. The story begins with a company that has designed a machine to fill a market void. The machine has been designed as two primary modules (1 and 2) using a well-orchestrated team split across the two modules. After prototyping the modules, they are tested individually. The tests are resounding successes, and a fully integrated test is implemented. During the testing, the overall product performance is not achieved at all. The modules simply interact to produce erroneous results. After many attempts at debugging, evaluation, and improvement, no advances are made in the product performance. The design team surrenders and becomes distraught as product milestones loom ever so close.

The team decides to hire an outside consultant to review the product and suggest possible failure modes. A well-known product designer is hired, reviews each module with the design team during a single one-day visit, and tests the integrated product. At the end of the day, after some contemplation, the consultant calls together the team, takes a piece of chalk, and marks an "X" on the module interface of Module 1, explaining the failure mode that is suspected. The consultant leaves, and sure enough, the team explores the "X'ed" feature, and corrects the fault. The product now works as expected.

A week later the team receives a bill for the consultant's services. The bill simply reads "Invoice for Consultation, Fee $100,000." Before paying the bill, the team asks the consultant to itemize the bill. A follow-up letter is received with the following itemization: "$1 for piece of chalk to mark "X", $99,999 for knowing where to put it. . ."

The moral of this story is that experience and intuitive insight/estimation are key characteristics of product designers, but also that clear, logical thinking permits insight. We must experience design to be designers. However, our ability to obtain experience is just a "blink of an eye" in the scheme of all possible design tasks and problems we may encounter. It should have been obvious to the separate design teams that interfacing was the problem—both teams had made false assumptions about the other. With structured design methods, this fault would have been clearly recognized and either avoided or overcome. We thus need methods and techniques to help direct our efforts when particular experience cannot be obtained or referenced. We begin to explore such methods in the next section.

III. MODERN PRODUCT DEVELOPMENT

In the subsequent chapters of this book, we present an integrated set of structured methods developed in conjunction with a host of industrial partners. Our approach focuses on the design of products and their constituent assemblies. The process begins with a design task and generates a functional model that culminates in a product specification. Later subprocesses build on the functional model and specification to execute the product development process.

This process is one that we have developed and to which we organize all the material of this book. Each chapter basically takes each of these steps, fully explains them, and then presents current state-of-the-art methods to accomplish the task. Therefore, to effectively explore this book, one should buy into the product development process outlined here or a facsimile of it. Through this exploration, the reader's personal design process will begin to mature and flower. It will be based on conscious forethought and introspection instead of the daunting limits of trial-and-error experience.

The remainder of this chapter initiates the journey into product development. First, to provide an industrial context for the engineering student, a typical *stage-gate* engineered product development process is explained as a comprehensive set of activities. Then, processes from certain companies clarify the process steps and illustrate their application by design teams in industry. Then we introduce companies from other industries with product development processes that are arguably much different and discuss how they are different and how they relate to the one discussed in this book.

Every company has a different development process out of necessity; there is no single "best" development process; *the design process* and *the product development process* are misnomers. The sophistication of the product, the competitive environment, the rate of change of technology, the rate of change of the system within which the product is used: These and many other factors that shape a product development process change for different companies. This change leads to different levels of speed, analysis, and sophistication required for the different tasks of product development as discussed in this book.

Xerox Corporation, producer of office document systems, and the Design Edge Company, a small design-consulting firm, apply a product development process much as developed here. On the other hand, Raychem Corporation, producer of advanced materials, has a longer research-intensive development process. Ford Motor Company applies the methods of this book, but does so hierarchically to the large system development required of a vehicle. We will also look at the very rapid development process of Microsoft Corporation, and the technologically intensive development of Hughes Electronics Corporation.

Some may feel that particular industries are special, and therefore the methods espoused in this book do not really apply to their engineered products. We will show how this attitude is typically presumptuous and false by discussing the varied companies previously mentioned. Our main source of information is our personal experience and observations while working with their products and engineers, working on many product development research interactions, and/or during on-site visits. Characterizing any company as following any particular process is, of course, a dubious task, since design processes always change: Lessons are learned, new processes for various tasks are developed, new design process technology is introduced, and the goals of a company change. Nevertheless, each scenario will paint an industrial snapshot in time, one to consider, ponder, and debate.

Students of engineering design should take away the point that every corporate circumstance is different, and so every company's engineered product development process will be a different sequence and level of application of the methods presented in this book. Further, each product development process changes over time in response to technological and market forces. Every engineer is always obligated to find an appropriate process and to always improve on it.

A Modern Product Development Process

Product development is a process: There are tasks of creating, tasks of understanding, tasks of communication, tasks of testing, and tasks of persuasion. At its highest level, we characterize any product development process with three phases: *understand the opportunity, develop a*

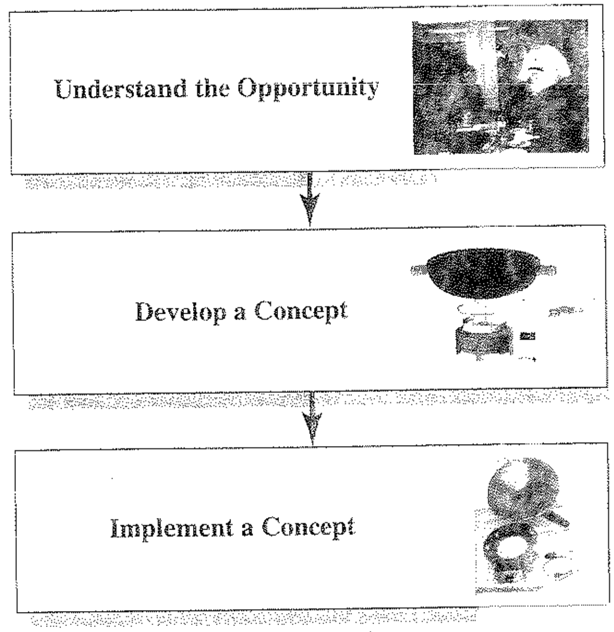


Figure 1.2.
Phases in a product development process.

concept, and *implement a concept*. This characterization is outlined in Figure 1.2.

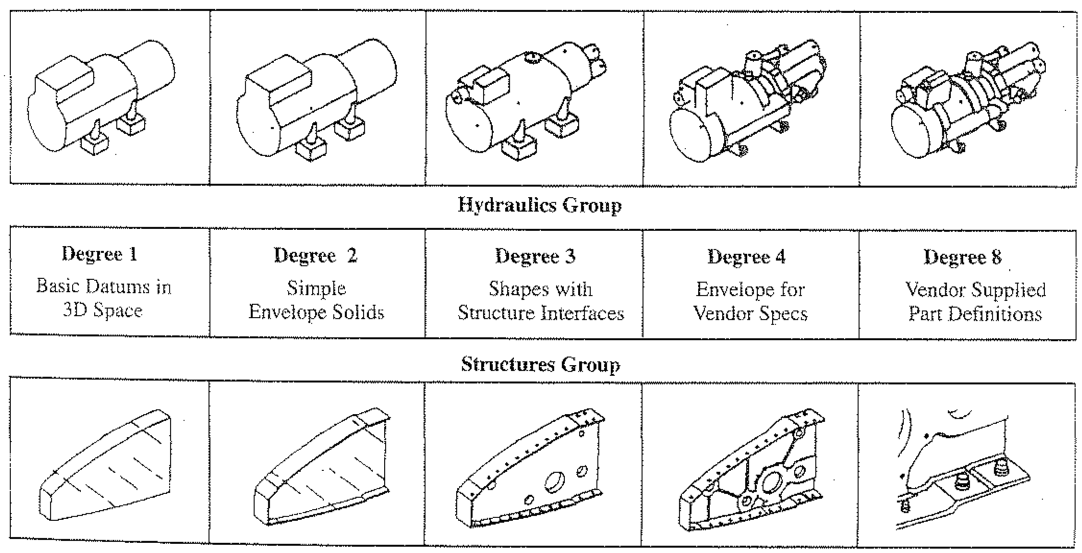
The first phase encompasses all activities needed to make the decision to launch a new product development effort. The second phase encompasses all activities to make the decision on what the product will be. The final phase encompasses all activities to make every product work well all the time. After the final product development phase, the product is ready to be manufactured. In reality, these phases overlap and are complex; yet, they help us to categorize the efforts needed to develop a product, and like all categorizations, there are counterexamples, and the boundaries are fuzzy.

The Stage-Gate Development Process

A product development process can be thought of as a sequence of parallel and serial *activities* or steps to be completed. Within any phase, there are concurrent development activities that occur. Mechanical design proceeds in parallel with electrical design in parallel with software code development. To ensure compatibility of these activities, many companies force the periodic "assembling" of the

product as it stands at a given point in time, along with its associated forecasted systems that remain uncertain (such as production, distribution, etc.). This assembly process is executed to obtain a better picture of the design as it is evolving, to evaluate that preliminary system, and, most importantly, to *freeze* parts of the design. Thus, some development decisions are made final at this point, such as general layout, user operation/interface, control, suppliers, etc.

This development process is known as a *stage-gate* process, or *waterfall* development process, where there are *stages,* or phases, or activities in the development work, followed by periodic gates. A *gate* is an evaluation by upper management or within the team structure to ensure the next stage is worth carrying forward. Any product development project must pass through each gate to make it to the point of product launch. Early gates, such as the end of the product definition phase, ensure there is a market for the product, and that it can be developed and manufactured. Later gates ensure "detailed" integration factors, such as ensuring that the software functions with the mechanical hardware. As an example, Figure 1.3 shows the states of completion required at different stages for different development disciplines within Boeing Aircraft Company's product development process.



▼ *Figure 1.3.*
Development degree-of-completion required for different stages at Boeing (Manente 1995).

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As shown in Figure 1.3, stage-gate processes often become very well defined within a company and so permit relatively rapid and reliable execution of the product development. For each gate, the required information that must be assembled is explained beforehand, and typically the product manager (the person in charge of developing the new product within the company) must assemble it and make the case to continue its development. Senior management then evaluates this information and makes a decision.

At each gate, the decision to be made is whether to proceed with the development and its direction or whether to "kill the product" (halt development) or certain features of it. A third option occurs when there is insufficient information to make this pass/kill decision. In such a situation, the decision makers determine what further development or investigation is required to make the decision and what target level the product must attain to either kill or pass it.

In practice, gates operate a bit differently. Typically, few projects are killed outright in the later stages. Instead of halting a project, specifications are revised in light of the development difficulties, and budget allocations are typically expanded. The product managers ask for more funds, and upper management debates the pros and cons. This scenario, of course, requires reanalysis of a revised business case that must be developed before the gate is entered.

Other models beyond a stage-gate process include a so-called *spiral model* of product development. This model is typical in time-compressed industries, such as software products. Here, one repeats the stage-gate process several times before finishing the product to 100% completion, where at the end of any of the stage-gate processes, one has a partial product that "works." It may not be fully featured, but it works.

For example, one could set up a development process for a word processor where the first pass around the spiral is a stage-gate process whose result is a design that simply edits text and saves/opens files. This result is a semicomplete design that works. As a "product," it could then be revised to be capable of different fonts. The revised design is semicomplete and works. This "product" could then be revised to include a spell checker. And so on. This process simply represents a chained set of stage-gate processes, except that during any of the stage-gate processes, the major development criteria also include compatibility considerations with the next product revision. For example, knowing that the next revision must include capability of colored letters may impact how a team designs a data structure to represent letters in the current revision.

Spiral models are effective in time-compressed industries with large uncertainty. Here, an effective strategy is to develop something—anything—to seek user feedback early, before major gates are passed and parts of the design become frozen too soon. Spiral development processes are not as typical in traditional mechanical product design, because mechanical products will not function at all until almost completely designed. For example, a car won't transport any person if it doesn't have a chassis, powerful engine, powertrain, and so forth. Designing only part of the hardware, such as just the steering or just the powertrain, is not designing a complete vehicle that could work. Even though each is developed as a subsystem, its development is not independent of the others. In integrated mechanical/software system development, one often sees hybrid spiral/stage-gate models for the various subsystems being developed.

Given these differences, it should be clear that enumerating a product development process in any more detail than shown in Figure 1.2 would result in discrepancies in its application. That is, if the "Develop a Concept" phase is described as a sequence of activities, then that sequence of activities will depend on the product being developed. Therefore, it is virtually impossible to develop a detailed description of "*the* design process" that will be general to all industries. Nevertheless, it is instructive to consider a typical and effective sequence of activities that one can expect in a product development process. Our view of such a sequence of activities is shown in Figure 1.4. This process is a typical sequence of design activities that will be encountered by any mechanical engineer.

Understand the Opportunity

The first phase, "Understand the Opportunity," we characterize with four activities. The first step in a product development process is often to have a vision for a new product. What product do we wish were out there? What is difficult with the current product we use? Why does it not do something we want it to? The answers to these questions are visions for a new product.

Visions are a dime a dozen. Everyone has an idea for a new product, every user has thoughts on how they wish their devices would work, every CEO has a vision for command of a market, and every research scientist has a vision for how their technology can be applied. The question is whether any vision can be transformed into a successful realization. Can it be developed and implemented into a product at a

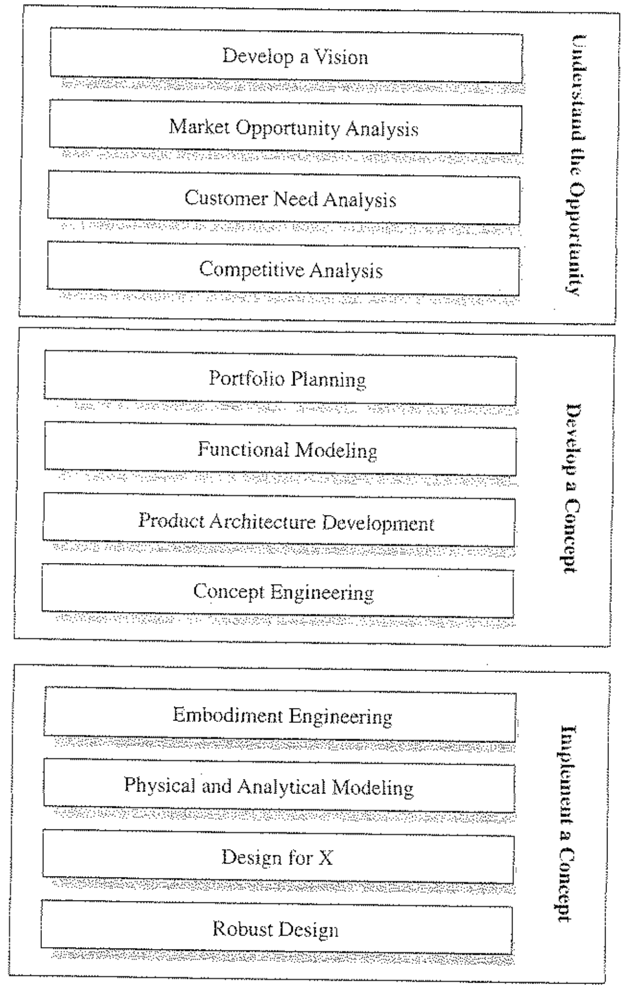

Figure 1.4.
Activities in a typical product development process.

worthwhile profit? The first part of this question is the market opportunity. The revenue that might be extracted by a new product from a market has to be estimated. In today's competitive environment, the estimated price and volume that a market will carry is always the starting point. From these estimates, a profit must be subtracted, defining cost constraints that a product must be designed to fit within. Methods for carrying out this analysis are developed in Chapter 3.

Having completed the market analysis and made a decision to proceed to develop a new product, a development team next must analyze and understand what the customer population wants the new product to do. Methods for understanding the customer are developed in Chapter 4.

Once customer needs are understood, the competitive products on the market must be analyzed in terms of how well they satisfy these customer needs. Chapter 7 presents methods for competitive analysis, using the teardown methods presented in Chapter 6.

At the conclusion of these activities, the design team understands the state of the competitive market, the customer population, and any available technologies. A gate evaluation can be made with this information whether to initiate development in the next phase; that is, to proceed in the development of a new concept.

Develop a Concept

Having clarified all available information on what a new product must do, how it must fit into the market, and what cost range constrains the product, the design team can work to meet these expectations. The first activity in this effort is to design a set of general market specifications for the product. This activity must be undertaken with respect to the complementary set of products that the company has to offer. It includes thoughts on product positioning in the marketplace and portfolio planning and development. Chapter 8 develops methods on these topics.

Understanding the portfolio architecture, customer needs, and competition orients a design team toward the generation of a new concept. One of the first tasks in concept generation is to determine what the product must do to supply the customer satisfaction, independent of how it is implemented. This task entails the execution of functional modeling, developed in Chapter 5.

Having a functional model describing the inputs, outputs, and transformations that must happen for a product to work, there are several possible groupings of subsets of these functions into actual subassemblies. Developing the interfaces in the product embodies the product architecting process, developed in Chapter 9.

The functional model and alternative product architectures set the stage for very-effective concept engineering. Here, a product development team generates many concepts for implementing the functional specification. Concept generation methods are discussed in Chapter 10. After synthesizing many concepts, a design team must select one to implement. This selection process is discussed in Chapter 11. The result of this analysis is the concept to develop. Again, a gate can then be established to decide whether to proceed with this project.

Implement a Concept

Having selected a concept, it must be implemented, which is the final phase of product development. Much of this activity is *embodiment engineering,* where a chosen concept is given form through specification of components to purchase, parts to manufacture, and specifications for their assembly into the product. Basic methods of embodiment engineering are given in Chapter 12.

One important aspect of embodiment is *modeling,* the testing of new implementation ideas by physical construction—building it—or by analysis—numerically modeling it. Modeling is typically understood in terms of explaining physical phenomena, in the rich tradition of the physical sciences. In product development, we don't want to explain physical phenomena, we want to develop a novel product that will delight customers, fulfil our dreams, satisfy our ethical responsibilities, and make money. Therefore, we must consider modeling in the real-world context, the product development process, and demonstrate how it supports design decision making. This view of modeling is presented in Chapter 13.

Methods to actually make models of the physical processes in a product are often difficult to initiate and evolve for effective decision making, both for novices and even experienced engineers. Chapter 13 thus develops a methodology for constructing mathematical models of customer needs in terms of variables that a design team can change, using the customer needs, functional model, and teardown results of the earlier chapters.

Based on the developed performance metrics that reflect customer needs, one must use these metrics to select a preferred design configuration. Chapters 17 and 18 develop experimental methods to explore different configuration alternatives and to construct performance models. Chapter 16 develops methods of optimization to study the developed models and to help a design team select values for specific configuration variables.

In addition to the many performance-related metrics of a product, a design team has additional engineering specifications that their product must meet. These specifications are the discussion of the various *Design-for-X* methods, where *X* is one of these requirements. For example, Chapter 14 develops *design for manufacturing and assembly,* where methods are constructed to ensure the ease of manufacturing and assembly of a product. Chapter 15 develops *design for the environment,* to ensure that a product uses minimal-impact materials and operations.

One key factor missing in our discussion is the emphasis that a design team must place on making the product work *well.* Any handy untrained person can make *something,* but it takes analysis and insight to fabricate an *engineered* product, one that can be put together easily, where every product off the assembly line works properly, and where each works well in varying applications and conditions. Ensuring this quality view of a product is the goal of *robust design* discussed in Chapter 19. The philosophy presented in the chapter should be applied to every activity in the product development process.

At the end of this phase, a working prototype exists. Often, production planning and manufacturing process design are also underway. These activities represent the final point in the development to establish the final gate, to determine whether to launch the product. Killing a project at this point is not done without consternation, since the project should not have proceeded to this point if it is to be killed. Though it is rare, if the return on investment looks low, changes are made to reduce costs, and the product is launched. More often, the prototype result performs as expected and particular features that offer strong delight are demonstrated and highlighted for advertisement at launch.

A Reverse Engineering and Redesign Product Development Process

Given the vision of a typical product develop process shown in Figure 1.4, one might be curious why the chapters do not follow this outline. Recall there are many product development processes, each tailored for the many different products and the many different cultures and experiences of different companies. We believe the way to learn product development is to do product development, but this belief presents practical difficulties, as many of the activities overlap. Finding an appropriate sequence through the activities to learn them is difficult. Our approach is to present a *reverse engineering and redesign process,* one that starts with a product in the marketplace and a vision to redesign it for some perceived market defect or envisioned evolution. In this sense, reverse engineering entails the prediction of what a product should do, followed by modeling, analysis, dissection, and experimentation of its actual performance. Redesign follows reverse engineering, where a product is evolved to its next offering in a marketplace.

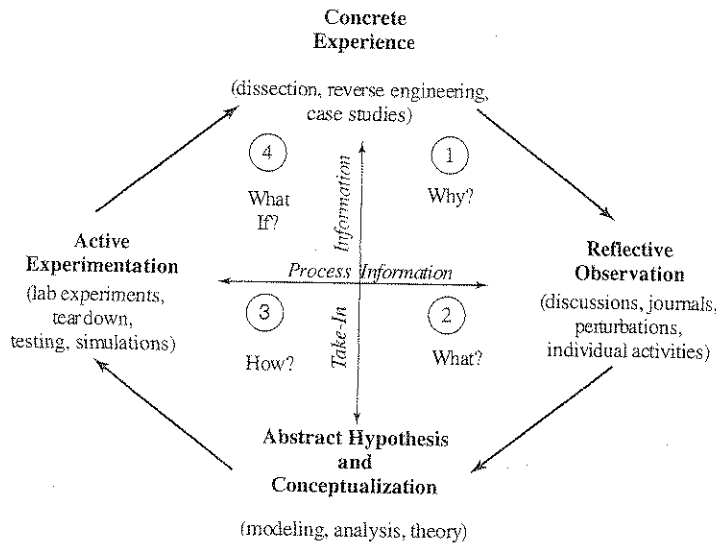

Figure 1.5.
Kolb's model of learning (Stice, 1987).

Figure 1.5 illustrates the motivation for promoting a reverse engineering and redesign process when studying product design. The figure shows Kolb's model of learning, embodied by a cycle that begins with concrete experience, proceeds with reflective observation and conceptualization, and ends, before restarting, with active experimentation. By redesigning a current product, the physical components may be directly experienced with all senses. Design methods may then be used to hypothesize current functions and conceptualize new functions and/or solutions to the current configuration. Observation and active experimentation with the current and refined concepts may then be executed, realizing mental ideas into physical embodiments. The process may then begin again, where further iteration enhances and cements learning as well as actual product improvements.

The Kolb model, as shown in Figure 1.5, swings the pendulum of learning engineering from an emphasis of generalization and theory to a balance with all modes of learning (Stice, 1987). Engineering becomes equally focused on hands-on activities. Without this approach, we have no concrete experience to ground our learning and build a solid understanding. Nowhere is this truth more pronounced than in product design. The grounding in a current product helps nurture our interest for understanding the way things work and for making devices work better.

Reflective Observation
(discussions, journals, perturbations, individual activities)

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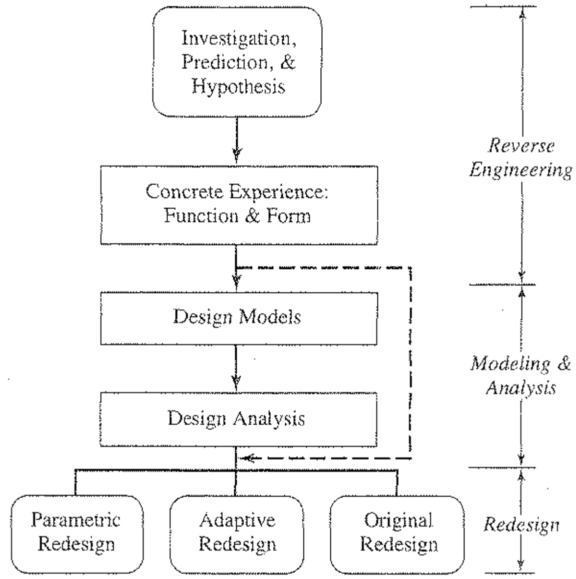

▼ Figure 1.6.
General reverse engineering and redesign methodology.

Figure 1.6 shows a general composition of a reverse engineering and redesign methodology. Three distinct phases embody the methodology: *reverse engineering, modeling and analysis,* and *redesign.* This approach allows us to present the necessary material on how to understand the product. For example, it is not likely that a design team will tear down their company's past product to understand how it works—they themselves probably designed it months earlier. Nonetheless, a student of engineering design who has not seen the past product will have to tear down the past design to understand it and will have to do so early. Such considerations lead to the order in which we present the material.

Given the ever-present guideline that activities overlap, Figure 1.7 illustrates an alternative sequence of reverse engineering and redesign activities for studying product development, still within the basic premise of three phases for product development shown in Figure 1.2. For the reverse engineering and redesign product development process, we rename the phases *reverse engineer, develop a redesign,* and *implement a redesign.* Let's consider each of these phases in further detail.

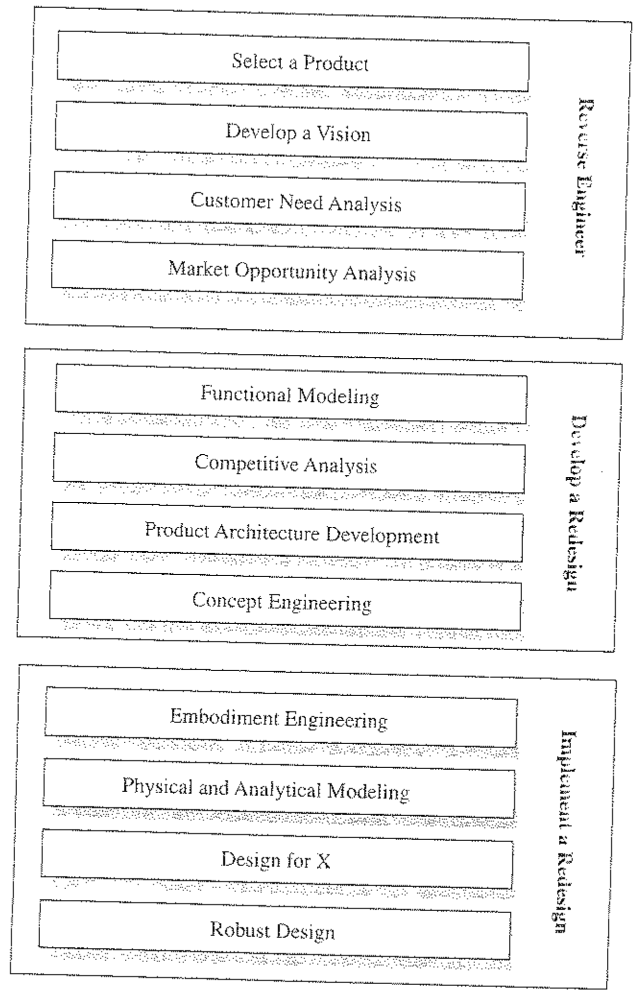

Figure 1.7.
A reverse engineering and redesign product development process.

Reverse Engineering

A reverse engineering and redesign methodology begins with a current product. For something to be redesigned, it obviously must preexist. A product that is in the market is well engineered at some level and so makes a good starting point to begin to understand the methods and activities in product development.

One of the first tasks is to understand the market for the current product. Customer needs analysis, as described in Chapter 4, searches

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for knowledge. This analysis culminates with an understanding of what the customers like and don't like in the product. Based on this understanding, a variety of redesign opportunities will be apparent. One can then complete a business case analysis as in Chapter 3. A business case will define the potential financial gains and risks of pursuing the redesign opportunities.

The next step in our reverse engineering and redesign process is to make intelligent estimates as to what the functional model ought to be, using the modeling in Chapter 5. This step is important to clarify our preconceived notions of how the product ought to function and to adopt a functional view of the design task.

The next step in our reverse engineering development process is to dissect the product and understand how it operates to satisfy or not satisfy the customers. The material in Chapter 6 can be used to help in this process. This reverse engineering activity can also be repeated for many of the competitive products, with additional literature searches on the marketplace to refine the business case. Chapter 7 discusses techniques to support these steps.

Based on the teardown of several products in the marketplace and related products of the manufacturer, the portfolio architecture of the manufacturer's product line can be analyzed, as discussed in Chapter 8. Shared systems among products can be clarified.

Understanding the component and system technology of the company and its competitors, a real/actual function structure for the product can be developed, using the methods of Chapter 5, where the results are compared with the hypothesized structure before teardown to explore preconceptions for superior approaches. The product architecture can be detailed on the function structure, as discussed in Chapter 9.

Develop a Redesign

After reverse engineering the product, new concepts can be explored using one of three redesign strategies. The existing product topology can be maintained and a parametric redesign explored—changes in thickness or geometry of components or changes in materials. Alternatively, the components can be replaced or placed in different topologies of the functional model. Finally, the entire concept can be replaced with a different functional layout or with different core technologies.

There are several tools and methods in the subsequent chapters that can be used to support any of these redesign approaches. First, Chapter 10 presents material on developing new ideas. Chapter 11 presents material on selecting among these ideas. At this point, a redesign strategy and a new concept in that strategy have been developed.

Implement a Redesign

Chapter 12 then begins the study of implementing the new redesign idea. Here, material is presented on how to embody a concept. Chapter 13 presents material on one important aspect of doing this effectively, modeling of performance related to customer needs. Chapters 14 and 15 present particular models that all effective mechanical designs must include beyond performance models of the product.

Chapter 16 then presents material on using models to select highly effective design configurations. Chapters 17 and 18 add to this discussion with experimental methods to accomplish the same goal but with physical models. Finally, Chapter 19 presents robust design material that should be used at every activity in the development process and specific methods that can be used to improve the quality of the embodiment developed up to that point.

Overall, unbiased prediction, customer-driven design, analysis using basic principles, and hands-on experimentation are the philosophical underpinnings of this redesign methodology. The intent of the methodology is to be dynamic, depending on the needed evolution for a product. For some product redesigns, it may be appropriate to perform adaptive or original changes before creating and optimizing a design model. Similarly, the model development of phase two may lead to a better understanding of the product, bypassing parametric redesign and leading directly to adaptive. Alternatively, another product redesign may call for simple parametric modifications to produce dramatic responses in quality and profit margin. This methodology may be used for any of these scenarios or others.

These thoughts illustrate a reverse-engineering-based design process using the material of this book, one that has been tested at several institutions with success. Still, it remains but one sequence through the material; indeed, depending on one's goals, many other sequences could be sensibly applied. One underlying theme of any sequence is to strive to apply the methods *fully* at least once, including wrestling with the details and analysis. Only then can one really understand the extra benefit that one gains through the extra effort, and as a result, one can make intelligent choices whether and how to reduce or even expand the modeling effort for any product development activity.

A natural response to this theme is that we really don't need to complete any number of product development tasks to the level described in this book. "We don't need to complete customer interviews, or we don't need to complete the house of quality, or we don't need to analytically model, or we don't need to trial experiment." Design is full of examples of "*don't need to*'s": It is the most common failure in product development, especially among novices and even among engineers who should know better. Avoid this trap, or learning will not take place and we will fail repeatedly.

At some point, we as engineers will design a product if we have not done so already. All product development processes are different, and it is important to form one's personal and intimate approach. In all likelihood, an engineer's livelihood and the livelihood of others will depend solely on how well one effectively forms that personal product development process. We no longer have any excuse for doing so blindly; we should design a product development process with intelligence and the background understanding and experience of what the *to*'s provide.

IV. EXAMPLES OF PRODUCT DEVELOPMENT PROCESSES

We now consider some industrial product development processes and show how they relate to the generic product development process of Figure 1.4 and to the material in this book.

Systems: Xerox Corporation

The Xerox Corporation is one company that uses a modern product development practice as discussed. Paul Allaire, CEO of Xerox, and Maurice Holmes, the corporate Vice President at Xerox, presented it as the Xerox "Total Time to Market" Product Development Process (1996), where the focus is on rapid time-to-market with a high-quality product. The Xerox Product Development Process is shown in Figure 1.8.

Note the steps in their self-described product development process follow Figure 1.4. The first step is to develop a vision for the market and the product strategy. This process develops a concept for the product family: the platform, how many products are part of the family, key technology components making up the platform, and the

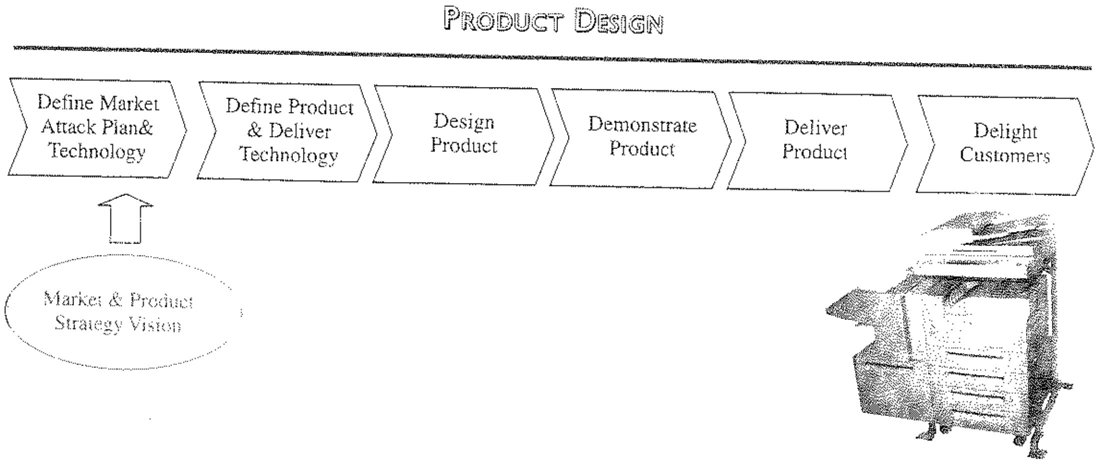

Figure 1.8.
Characterization of Xerox's Product Development Process and an example copier.

expected business outcomes. This vision is developed by senior management as part of the yearly corporate planning process. For example, in the early 1990s, Xerox management envisioned a marketplace that was transformed by computers and networks into a digital document environment—information was created from a combination of digital or paper sources. It was distributed over local or enterprise-wide networks and printed at the point of need in monochrome or color. The Xerox copier would therefore be transformed into a digital document machine. This device could copy, print, fax, or scan a document to a file over communication networks, enabling customers to achieve higher levels of office productivity at much lower cost of ownership. To realize this vision, the entire office product line from 12 to 65 pages a minute would be changed from analog copiers to digital document centers through the development of many new product families derived from two new product platforms. Light-lens optical technology would give way to electronic scan bars and raster output scanners. The dominance of Xenographic and electromechanical technology would give way to network controllers, PDL decomposition, raster input scanning, and data compression and decompression technology. This change would in turn be accompanied by changes in manufacturing, service, and distribution as required by the needs of the new digital market.

The next activity is to develop a plan for the particular product in the family. This step defines the market opportunity for the product.

Xerox terms this the *Market Attack Plan;* senior management again develops it. A case is made for a new product line opportunity, typically involving several products that are part of a product family supported by a product platform. Such a business case analysis to determine how to launch a product is developed in Chapter 3.

Individual products are only developed within the context of platforms. The process itself is a sequence of activities that is ostensibly repeated for every new copier development project, but with ever-advancing technological components and ever-advancing design process technology. Such a product platform design is discussed in Chapters 8 and 9.

A product platform is a system of key technological components (platform elements) integrated to form products according to a set of architectural rules. This system includes, for example, the print engine that actually marks ink on the paper, the paper delivery system for feeding paper to the print engine, the user interface, machine controller, network controller, and so forth. Each of these components is a heavily invested-in piece of core technology that Xerox considers a market advantage. For example, the departmental document center document scanner contains a butted silicon scan bar that allowed the scanning of paper documents at far greater speeds and resolutions than typical LCD arrays used in competitive devices. This scanner was used as a platform element for Docucenter 40, Docucenter 55, and Docucenter 65 digital copiers and scan-to-file products.

At Xerox, the product design itself is completed using methods discussed in this book. For example, functional models as discussed in Chapter 5 are applied using a block diagram methodology. The house-of-quality tables presented in Chapter 5 are extensively used. Robust design presented in Chapter 19 is a methodology and philosophy used throughout the design process. The design itself is demonstrated in development with prototypes and mockups and by using performance metric models.

Throughout the development, Xerox also pays strict attention to design process metrics to ensure the development process itself is well designed. This attention to constant design-process improvement is very important to Xerox. It operates in a competitive environment where reduction of development time is critical, since new electronics technology is constantly being developed that impacts Xerox's markets. Methods to ensure good process are discussed in Chapter 2.

In sum, Xerox exercises a well-developed product development process. The activities in the process are developed in this book, and they practice the methods espoused. Further, they are always seeking more rapid, higher performing methods to increase their competitiveness.

Industrial Design: Design EDGE, Austin, TX Product Design Firm

Design EDGE is a product design firm that develops products for a number of industrial clients. Figure 1.9 illustrates a snapshot view of the product development process executed by Design EDGE. The figure lists the major steps in the process in addition to tools that are used to support the development steps. Figure 1.9 also shows recent results (1998) of novel products created from this process and the designers of Design EDGE.

Notice that the process embodied in Figure 1.9 again satisfies the general structure of the process of Figure 1.4. After being approached by a client company, Design EDGE begins the process with understanding the design task, based on customer and client interviews, market analysis/data, and initial clarification of the task through studying functionality, needed attributes, and the feel desired in the product.

The development process then transitions to a focused effort on preliminary concept development. Industrial designers lead this effort with a clear team emphasis, including engineering and industrial design team members. The tangible result of this phase is a product proposal to the client illustrating a number of industrial design concepts and the associated development costs and schedule for executing the designs.

Assuming the client company adopts the proposal, product development now turns to implementing a product concept. Two layout stages comprise this phase: Industrial designers lead the first stage and engineers lead the second stage. During both stages, the goal is to refine the product concept in form, shape, feel, and technical component issues of technological choices and performance. The product team balances physical prototypes and numerical models to make decisions concerning these issues.

To further implement the concept, product tests are performed. These tests are followed by refinements, culminating in tooling design for full-scale product production. Databases and prototypes are transferred to the client as deliverables (after approximately a 6–18-month ıct development process. :his book, and they prac- ways seeking more rapid, ompetitiveness.

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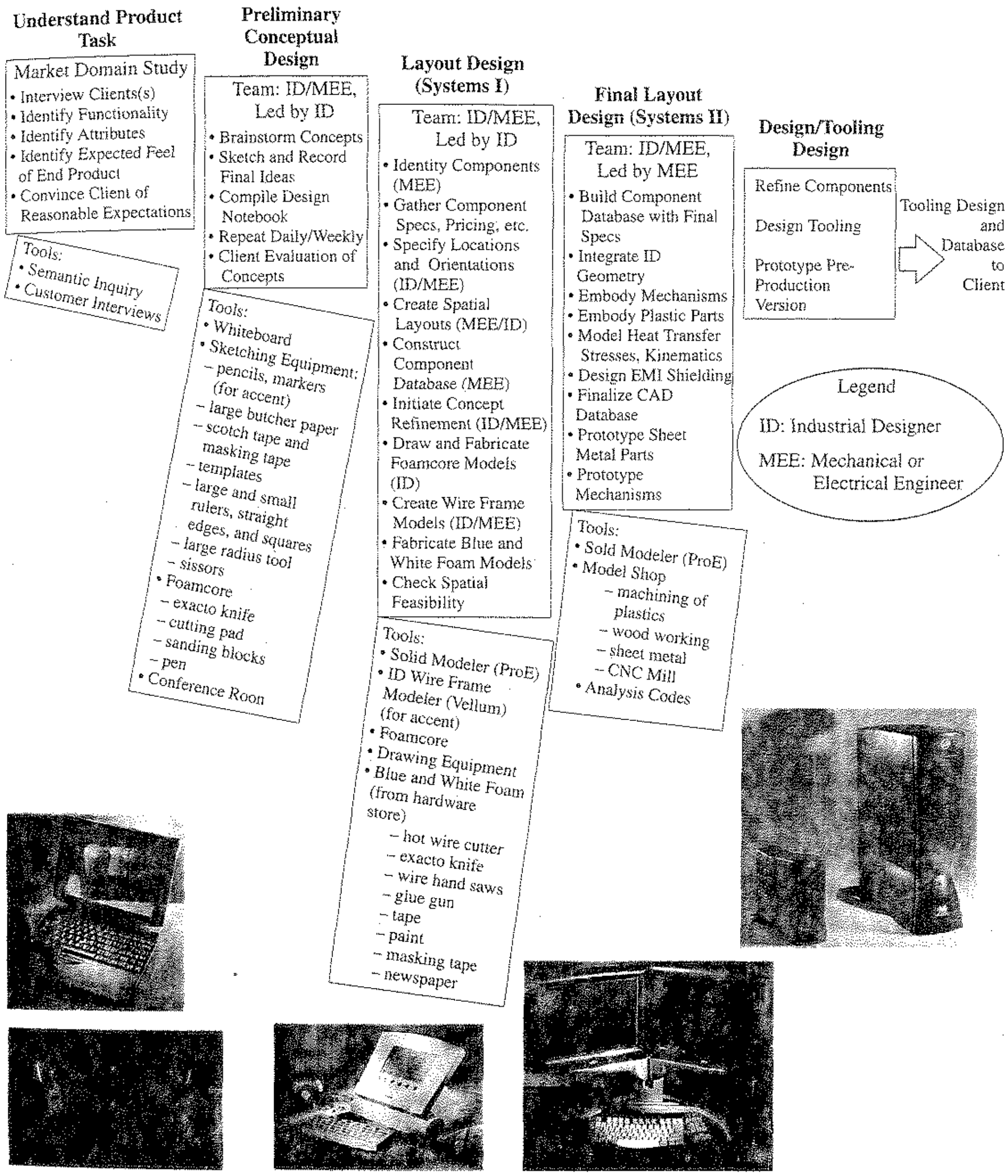


▼ *Figure 1.9.*
Characterization of the Design EDGE Product Development Process and example products.

development cycle time), and the client carries the process forward to production, packaging, marketing, and distribution.

Again, the Design EDGE process is very similar to our generic methodology for product development. It includes clear stages of understanding, conceptualizing, and implementing. A number of interesting distinctions do exist, however. For example, Design EDGE stresses a strong emphasis on industrial design. Product feel and expression are critical to consumer products. Design EDGE addresses this issue head on, driving the initial product layouts with the artistic and ergonomic features of industrial design.

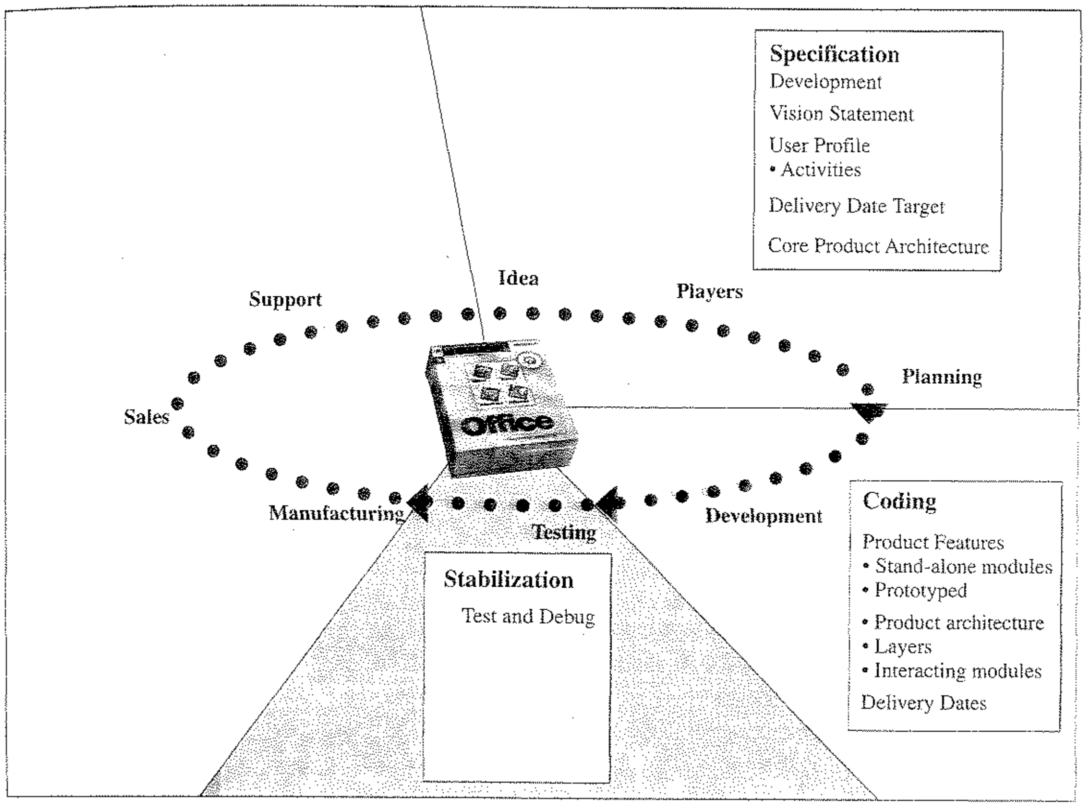
Rapid: Microsoft Corporation

Some companies live in a competitive market cycle that is much faster than was just considered. In fact, some exist in technological change cycles that are so fast that the generic development process of Figure 1.4 cannot be entirely completed. Some steps have to be short-changed, or the company will not introduce its product into the marketplace soon enough.

For example, Microsoft Corporation develops software and must do so very quickly. Microsoft Excel version 5.0, for example, was completed in 18 months with as many as 125 people working on the project (Cusumano and Selby, 1995). To meet this schedule, some of the development tasks are abbreviated. For instance, Microsoft does not have an extensive program to interview customers and determine what they like and don't like in a product. Rather, Microsoft relies on a strategy of having a flexible product architecture, understanding the uses of their product, and designing to a delivery schedule.

The product development process of Microsoft can be linearly characterized with three phases: planning, to develop a product specification and development; coding, to complete the coding; and then stabilization, to debug the code. However, Microsoft views its process more of an ever-cycling development process, better described circularly. That is, while finishing one revision of the product, they must necessarily be thinking forward to the next revision. This process is shown in Figure 1.10 (courtesy of Microsoft), with the three key development phases highlighted.

The first phase in Microsoft's development process is as the others': understand the problem and create a specification for the development task. *The Specification Document*, developed by senior management, starts with a vision statement, itemizes it into outline form, and then defines and assigns priorities to new or enhanced product features.



▼ *Figure 1.10.*
Characterization of Microsoft's Product Development Process.

The vision statement is viewed as key. Chris Peters, Vice President of Office Product Unit, states, "A good vision statement tells you what's not in the product, a bad vision statement implies everything is in the product" (Cusumano and Selby, 1995). An example is the MS Office products, where the emphasis of the vision statement was on harmonious use of the multiple desktop applications rather than as a jumble of applications that the user has to determine how to get to work together. Product managers then must refine this choice. With marketing, they develop potential features.

This step is refined based on user activities and data. That is, Microsoft does listen to the customer as espoused here, but in a rapid-response manner. Rather than asking customers for product preferences, Microsoft interviews customers and studies the tasks that people use with the software applications. They uncovered, for example, that many people use Excel for creating budgets and Word for writing letters. They then carried out studies and broke down into activities what is needed to complete these typical tasks.

Features are selected for inclusion in a product based on how they impact these user activities. Thus, Microsoft doesn't carry out interviews on the past product *per se;* rather, they perform market studies of how people work. Microsoft then estimates how new features will impact these use times and estimates market acceptance. If they get it right, the new product feature is a hit. If they guess wrong, the feature is a dud. They do not have time to ask the customers directly.

The specification document typically grows and changes 20–30% from start to end of the project. John Fine, group program manager for Excel, describes how the specification document should be written: "All is from a user's point of view. That's everything—just never worry about anything else except 'What does the user perceive?' When you use a product, what the product does should be understandable enough so that any user can say in a sentence what it does" (Cusumano and Selby, 1995). Clearly, Microsoft understands the need to listen to the customer.

The second phase of Microsoft's development process is to create the code. Here, they develop each module separately as a Visual Basic™ prototype. This prototyping process proves the feature, they then work to integrate it into the product. Key to this modular product philosophy is a flexible product architecture based on modules with standard interfaces, with a flexible common platform core. Every product has a layered platform, which is the inseparable core of functions that a product must perform. They devote considerable time and resources to this step so that the job is completed with high quality.

A key aspect of the rapid development process is to design to a schedule. Here, every activity is given a schedule. They time-delimit each activity, and within that time allotment, every programmer evolves features as much as possible. As expressed by Chris Peters, Vice President of Office Product Unit: "If things don't work out, I'll just cut features I think are less important" (Cusumano and Selby, 1995). They do not extend the schedule and include features as the first development process choice. They can always add the feature into the next revision.

The last phase in the product development process is stabilization; here the focus is on testing and debugging. No new features are added, but rather the product as a system of features is made to work together all the time, that is, to be robust as discussed in Chapter 19.

During this phase, a further key aspect to Microsoft's customer interactions is the use of the customers' feedback during development.

Microsoft has an extensive beta-release network of users, who receive preliminary versions of software to test-run them as a part of the code stabilization phase. This provides excellent feedback and opportunity for adjusting the product before release.

The Microsoft development process does not negate the process of Figure 1.4. Microsoft's activities are the same but are optimized to permit task completion in very short time. The focus of this textbook is to understand what the activities must do, and it presents methods to execute each easily and completely. If one seeks to shorten the cycle at the expense of completeness, one has a basis for making that choice and understanding the ramifications. The rapid result philosophy is appropriate for Microsoft's marketplace—they have to develop products very quickly.

Research Intensive: Raychem Corporation

Some products exist in development cycles much longer than that considered above. The product development cycle may become so long that it becomes difficult to forecast any customer wants and needs. The Raychem Corporation, for example, is a sophisticated manufacturer of products utilizing advanced materials. Historically, they have developed products based on new materials research. Their product portfolio includes heat shrink tubing to easily bundle wires, GelTek(TM) moldable electrical sealants, arresters that help protect electrical devices from the dangers of surges, and resettable fuses that protect cellular phones, speakers, and batteries from electrical overload.

Some of these products took decades to develop. For example, the PolySwitch(TM), an electrical overload cutout switch made from a polymer, was first conceived in the 1970s. After several years of R&D, the first prototype was built in the lab in 1981. The first product hit the market a few years later. Yet, the product did not pick up sales until about 1990 and was not really a success until the mid 1990s, when it became a standard component in every laptop computer battery pack. Now the product is widely used and very profitable. How is such long-term product forecasting and technology planning done? What specifications should be considered for a switch, where the product may not be commercially successful for decades? What will the world look like in decades? How could anyone in 1970 forecast the need for a polymer overload switch in laptop computers in the late 1990s?

Obviously there is a bit of luck involved, but not as much as would first appear. With the constant exponential growth in electronics, it was reasonably clear that inexpensive, low-weight, easily produced polymer switches would be in high demand. The issue was whether the polymer chemistry could be reasonably worked out and packaged. Raychem is a high-technology company; its core competency is in working with high-technology materials. This skill is its competitive advantage, which enables Raychem to make materials do most anything: The key is to get a material to do something that will be profitable.

Raychem develops a suite of different products that can require a varied amount of development; some are intensive in determining how to apply a new material, others are rapid applications of existing technology. Even with the high-technology products that incorporate longer cycle new technology development, though, Raychem applies a structured stage-gate product development process; its self-described process is diagrammed in Figure 1.11.

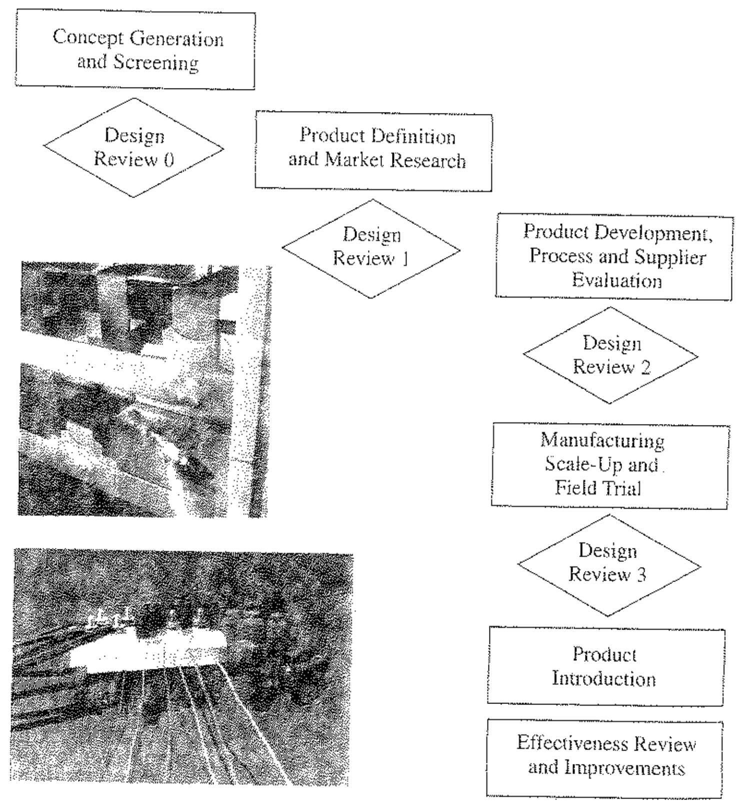


Figure 1.11.
Characterization of Raychem's Product Development Process.

The Raychem Product Development Process starts with a vision to fulfil a perceived market need with a new product that Raychem believes it can develop. This is typically initiated through discussions with the customers by the Raychem sales force. Raychem prides itself on having a tight relationship with its customers, always probing for opportunities. They have a saying in the company of "Raychem in Response," meaning the company listens to and responds to its customers.

In the early 1980s, one of Raychem's telecommunications customers asked a salesperson if Raychem could develop a product that would prevent corrosion of connections in outside-mounted terminals. This request was initiated in Raychem's develop process as a document presenting the design and business case, physically instantiated in the "Design Review Book," a documentation of the product to be developed as it is being developed. The decision to consider developing the product is made at the first review meeting, called "Design Review 0," by a design review committee. The committee consists of the Division Manager, Technical Manager, Product Manager, Market Manager, Manufacturing Manager, Quality Manager, and other specialists as needed, representing environmental, legal, and purchasing concerns. The go/no-go decision is made based on whether the product fits within Raychem's product strategy—can Raychem make such a product?

After Design Review 0, the market feasibility and business plan is fully developed and analyzed. The product function is precisely defined complete with technical specifications and customer-need statements. The costs are estimated, including material, manufacturing, distribution, and development costs. Returns on investment analyses are completed. Technical feasibility is agreed to.

For the corrosion-proof outside connector design problem, the customer need was communicated to a design team that evaluated a number of product concepts incorporating standard Raychem technologies. Unfortunately, none of these concepts met the customer's requirements. The design team then came up with entirely new concepts—the "Maybe we can . . ." scenario. The design team decided that a new soft, highly conformable sealant was required. At the next design review, Design Review 1, a technical assessment and business plan was evaluated, and resources were committed to develop such a new soft, highly conformable sealant.

After the Design Review 1, much conceptual and embodiment product design work ensued. The design requirements were flowed down to component specifications, concepts developed, and prototypes constructed and analyzed.

Successful materials development and product design work resulted in the introduction of Raychem's first gel-based product, the Termseal™ terminal cap. This terminal seal was a novel gel inside a plastic housing that could be squeezed conformably around a terminal, thereby sealing it. This concept was shown to many customers, and market acceptance and real-world performance assessed. These results were used in the last design review, Design Review 3, to make the final decision to launch the product full scale. Today, Raychem sells dozens of gel-based products throughout the telecommunication, commercial, and automotive electronics markets.

Raychem has many product families built on core technologies. The gel-based product family is one example. The Termseal™ product was Raychem's original gel-based product. From it, a suite of product variants has been developed into a product portfolio, as discussed in Chapter 8. The Geltek™ family of sealants is the latest generation, including products that provide EMI as well as corrosion sealing.

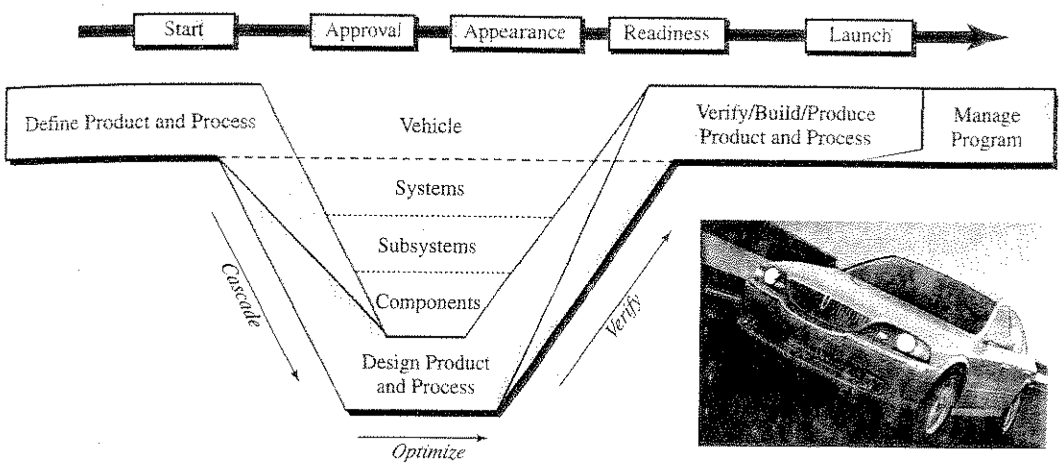
When Raychem first formed as a company, it operated with a "Cost +" approach: Manufacture the product, count up what it had cost, add a profit, and demand that as a selling price. With the high technology that customers wanted, they could afford to do so. As argued in Chapter 3, this approach is not always the most effective, and so for many years now Raychem has operated on a "value" approach. That is, first Raychem estimates the market price, and from that profits are subtracted to arrive at a design target maximum cost. Against this, feasibility is judged.

The main issue with Raychem has been to develop very advanced research-intensive products. They require significant material science and uncertainty in market acceptance. Nonetheless, at its highest level, the Raychem Product Development Process is a stage-gate process, much the same as other product development processes described in this book.

Complex: Ford Motor Company

Many products are complex assembled systems of many suppliers' components and subsystems that must properly function together. It might be argued that these products form a special class for which the methods in this book do not apply. As an example, consider Ford Motor Company, developer of automobiles and trucks. One can characterize their product development process as in Figure 1.12.

The Ford Product Development Process starts with the "Define Product and Process" phase to define specifications for the new product.



▼ ***Figure 1.12.***
Characterization of Ford's Product Development Process.

These are both soft customer criteria and hard functional specifications. These are first gathered at the vehicle level or by using attributes that are dependent on the entire vehicle system. These attributes are then cascaded down to individual systems, subsystems, and eventually components. The added complexity in these large-system products is the interactions between subsystems and the larger product itself and how these interface. The methods of the book can only help make these interactions clear.

In the "Design Product and Process" phase, the actual product components are finalized, including, in particular, how they will be assembled into the vehicle. Significant concurrent activity with manufacturing engineers is required. The "Verify/Build/Produce Product and Process" phase verifies the integrity of the product and process designs and ensures that no negative consequences arise from the interfaces and interactions of the various subsystems. The last phase, "Manage Program," is simply the collection of management tasks that ensure the capability of the program to meet its objectives—managing resources and timing and capturing into the corporate memory lessons that are learned.

The added complexity of this product development process is the subdivision of labor and product functions among the various subsystems. Generally, the tools of this book apply hierarchically, with different detail at the various levels.

Technical: Raytheon Corporation

It might be claimed that if a company's product line is very technical, then customer-, function-, competitor-, or experimental-based concepts do not apply. The communities that design electronics or design precision manufacturing processes often make such claims of "just needing good engineering."

A branch of the Raytheon Corporation, formerly Hughes Electronics, is recognized as a world leader in designing and building electronic systems for defense applications, such as missile guidance systems that can precisely and reliably direct a missile thousands of miles. They are a company that routinely does some of the toughest and most innovative engineering, which has included the development of the world's first laser.

Raytheon characterizes their technology-intensive product development process as shown in Figure 1.13. With Raytheon's defense industry products, there is little apparent market analysis, since there is no statistical population of customers to worry about. Instead, a typical defense product is characterized in terms of scenarios in which it will be used: a *mission profile*. For example, the Cruise missile is a typical product designed to a mission profile. Specifically, a cost-effective missile was described that would have precision strike capabilities which would minimize pilot exposure and minimize population causalities. This was described in a customer-military-approved document that launched the design activity.

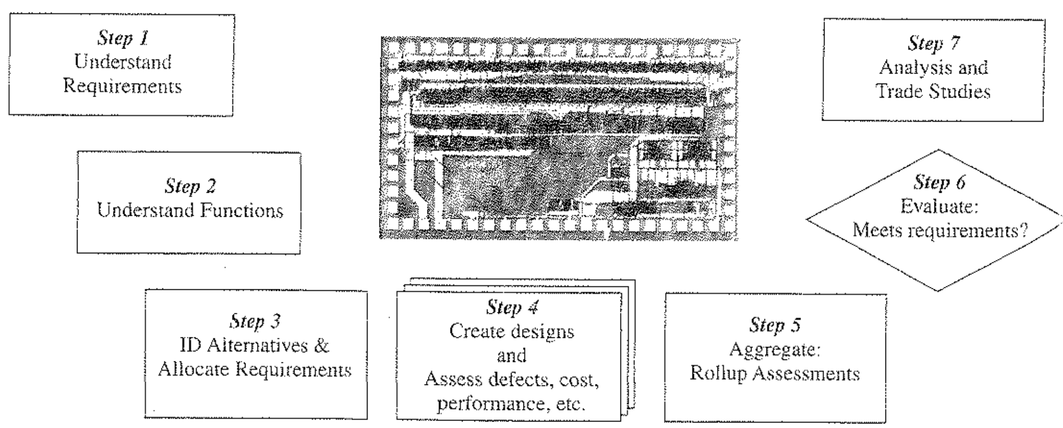


Figure 1.13.
Characterization of Raytheon's Product Development Process.

In the second step of the Raytheon Product Development Process, the mission profile is refined into functions for the product to complete. Overall system technical specifications are developed that the product will have to satisfy. In the Cruise missile case, the product required a long-range propulsion system so it could be launched from aboard ship hundreds of miles from a target, with a high-precision targeting capability to ensure target destruction without peripheral casualties.

With the technical specifications, a functional architecture of the product is developed. Then, in Step 3, a system layout and architecture is developed, and further subsystem requirements are allocated. For example, in the case of a fiber-guided air-to-air missile, the missile was divided into a product architecture of seeker, inertial components, ordinance, actuators, and propulsion systems. Each of these modules was then assigned further refined specifications on criteria such as power, mass, and size to ensure the entire missile would perform according to the mission profile.

With the functional and system architecture, subsystem concepts are generated, embodied, and designed as Step 4. During the subsystem designs, periodic system-wide "rollup assessment" meetings are held to ensure compliance with the system specifications, as noted in Step 5. These serve as gates in Raytheon's stage-gate development process. In this entire process, much modeling, experimentation, and optimization are completed.

Raytheon's main emphasis is on developing very technically advanced products. They require significant engineering resources and delicate manufacturing. The design cycle to complete the system design and allocate subsystem specifications is becoming much more rapid with computer-aided concurrent design environments, where multiple designers from different disciplines negotiate specifications while evaluating total system performance. Such systems will be shown in subsequent chapters. However, as shown by Figure 1.11, the process that Raytheon follows is much the same as other product development processes and is as espoused in this book.

V. THEORIES AND METHODOLOGIES IN DESIGN

There is a rich literature on mechanical product design. The methods and approaches presented in this book are a culmination of many persons' efforts and combined wisdom. To understand where these methods and thoughts arose, it is instructive to reflect on the history of mechanical design theory, from its very inception at the start of recorded history to the current state of development. Table 1.2 highlights 50 major design theory developments in world history, in the view of the authors.

As surmised from Table 1.2, design theory is not yet a mature field; new developments are constantly being undertaken. This insight is further understood from the plot in Figure 1.14. Two discernable trends emerge: One is the rich development that occurred up through the time of the Roman Empire, with a plateau around the first millennium. Then, another rapid profusion of design theory development began about the time of the 1700s, which has not let up to this day.

The first development period can be explained as the developments in design theory required of classic civilization, which ended with the fall of the Roman Empire. The advancement stagnated during the Middle Ages. Since craftsmen and architects were the designers of the age, they relied on the handed-down knowledge of ancient Greece and Rome for their understanding. Medieval civilization was, from a design theory point of view, no more complex than ancient civilization. Technology had not advanced significantly, so there was no demand for further developments in design theory. Grossly simplifying: Medieval civilization could develop all required devices with the handed-down design theories of ancient civilization.

It wasn't until after the Middle Ages that this trend changed; technology advanced and the need arose for better design theories. New production systems, new labor-saving technology, new understanding of the physical world, new mathematics—all of these advancements required more than a simple build-and-test design methodology. Complex devices had complex mechanics; this created a need for new design theories incorporating analysis and synthesis of these systems. This complexity trend has shown no signs of any plateau; design theory remains an active field.

It is also interesting to note the contents of Table 1.2, in particular that mechanical design theory is strongly rooted in kinematic theory. The first theories on the design of mechanical devices were basically kinematic. It is only recently that more modern thoughts are being applied from other fields, such as separating function and form when designing a complex mechanical system, applying complex algorithms to routine synthesis tasks, and considering the value that a feature will bring to a device concept.

Where can we expect new developments to occur in mechanical design theory? To answer this question, one must examine what is driving the need for development. As noted in the introduction, there

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TABLE 1.2. DESIGN THEORY DEVELOPMENTS IN WORLD HISTORY

Author	Publication title	Theory or development	Origin	Year
	The cubit	First measurement standard: Pharaoh's forearm plus his palm	Egypt	2500 BC
	Ebers papyrus	First design manual: description of making a soap-like substance	Egypt	1500 BC
Aristotle or Straton	Mêchanika	First known book on engineering: falling bodies accelerate, vacuum is the empty space between atoms, successive gears rotate in opposite directions, the lever and beam balance, compound pulleys, the sling, capstan, windlass, rollers and rolling friction	Greece	350 BC
Archimedes	On floating bodies, On the Equilibrium of Planes, De Mensura Circuli	Calculated pi to ±0.1, 2D center of gravity, hydrostatics and buoyancy; Archimedes law, levers and mechanical advantage, a planetarium, the dolphin; a hoisted missile dropped through a boat	Greece (Syracuse)	240 BC
Hero	Pneumatica (Pneumatics)	Siphons, sprinklers, fountains, steam jets for spinning; first concept of an engine, first coin-operated dispensing machine, check valve, float valve, water force pump with a nozzle, a steam-powered rotating ball, theory of compressible air, first description of a windmill, first discussion of weighing fuel before and after combustion	Alexandria	150 BC
Hero	Mêchanika (Mechanics)	Idea of moment and explicit mechanical advantage, Theory of kinematics using five basic machine elements	Alexandria	150 BC
Vitruvius, Marcus Pollo	Die Architectura libri decem	First design theory—considers design as satisfying human needs, in architecture	Roman	27 BC
Banu Musa brothers	The Book of Ingenious Devices	First description of a feedback control system (to supply an oil lamp at constant flow), description of over 100 devices	Iran	AD 750
Bhaskara		First concept of a perpetual motion machine	India	AD 1159
Walter of Henley	Treatise on Estate Management and Farming	First method of experimental techniques to optimize production output	England	AD 1300
Brunelleschi, Filippo	Patent	First patent, issued by the Republic of Florence, for a canal boat equipped with cranes. More important, in some respects, he is the person who invented perspective drawing	Italy	AD 1421
Unknown	Manuscript of the Hussite Wars	First science fiction (a diving helmet and a deep-sea diver), first depiction of a cannon	Germany	AD 1430
Da Vinci, Leonardo	Notebooks	First professional mechanical engineer; revolving turret mill, notes on armaments; bevel, spiral, differential gears; universal joint; cutting screws, sprockets and roller chains, hydraulics	Italy	AD 1488
Town of Nurmenburg		First industrial exhibition	Germany	AD 1568

TABLE 1.2 (CONT.). DESIGN THEORY DEVELOPMENTS IN WORLD HISTORY

Author	Publication title	Theory or development	Origin	Year
Stevin, Simon	De Beghinselen der Weeghcons	Triangle of forces: first description of vector math, permitted calculation of static loads on machine elements for the first time	Netherlands	AD 1586
Galilei, Galileo	Discoursi e Dimonstazioni matematiche (Dialogues Concerning Two New Sciences)	First discussion of the responsibility of a designer toward safety; first text on stress analysis in beams; mechanics: formalization of the concept of force and acceleration of bodies, vacuum	Italy	AD 1638
Newton, Isaac	Analysis per aequationes numero terminorum infinitas	Method of infinite series: generality and inverse nature of integration and differentiation	England	AD 1669
Gautier	Text on Bridges	First to complain in writing that the scientists of the day had no interest in practical matters (such as arches)	France	AD 1716
École des Ponts et Chaussées	Charter	First engineering school	France	AD 1747
Hume, David	An Enquiry Concerning Human Understanding	Famous presentation on the philosophical problem of inductive inference, a common thought process in design	England	AD 1748
Smeaton, John		First to call himself a civil engineer: non-military; first use of models to provide quantitative design information: tables of water wheel and windmill data	England	AD 1752
Euler, Leonhard	Recherches sur la veritable courbe que decrivent les corps jete dans l'air, ou dans un autre fluid quelconque	First application of Newtonian mechanics to engineering analysis; solution to differential equations of ballistic flight with air resistance, compared to Robin's experimental data	Germany	AD 1753
Bayes, Thomas	An Essay Toward Solving a Problem in the Doctrine of Chances	Bayes rule for deduction under uncertainty	England	AD 1763
LeBlanc		First to propose interchangeable parts	France	AD 1785
Maudslay, Henry	J. Nasmyth *Autobiography*, 1883.	Precision and accuracy as a machine design theory; Maudslay's Design Maxims: *Get a clear notion of what you desire . . . then you will succeed; Eliminate all material not needed . . . put to yourself the question, "What business has it to be there?" Make everything as simple as possible; Remember the getability of parts;* Standard screw threads; developed compound slide rest lathe; first use of a micrometer in a machine shop	England	AD 1807
Willis	Principle of Mechanism	Definition of a machine as a kinematic train	England	AD 1841

TABLE 1.2 (CONT.). DESIGN THEORY DEVELOPMENTS IN WORLD HISTORY

Author	Publication title	Theory or development	Origin	Year
Froude, William		Methodology of model testing; similarity theory and scaling from prototypes	England	AD 1869
Reuleaux, Franz	Theoretische Kinematik: Grundzuege einer Theorie des Maschinenwesens	Definition of a machine as a kinematic train that performs work; definition of kinematic degrees of freedom	Germany	AD 1875
Roebling, John	Final Report to the Presidents and Directors of the Niagara Fall Suspension and Niagara Falls International Bridge Companies	Reliable design theory: Reliability comes about by analyzing past failures for failure modes and designing past them; completed the Brooklyn Bridge in 1888	USA	AD 1885
Reynolds, Osborne		Mathematics of testing using scaled prototypes, of the silting of the River Mersey in Liverpool	England	AD 1887
Weber, Max	Wirtschaft und Gesellschaft	Theory of rational behavior (Rationalität)	Germany	AD 1904
Fisher, R. A.	The Design of Experiments	Most influential book on conducting experiments to optimize physical systems	England	AD 1935
Turing, Alan	Can a Machine Think?	Definition of a computer	England	AD 1936
Von Neumann, John & Oskar Morgenstern	Theory of Games and Economic Behavior	Modeling of single-person rational decision making	USA	AD 1944
Miles	Value Analysis	Theory of value as amount of function provided divided by how much it costs to deliver	USA	AD 1947
Zwicky	The Morphological Method of Analysis and Construction	First systematic tool for creativity	USA	AD 1948
Hansen	Konstruktions-systematik	Theory of design as a systematic step-by-step process	Germany	AD 1955
Altshuller	Theory of Inventive Problem Solving	First systematic tool to explore past inventions	Russia	AD 1956
Osborne, Alexander	Applied Imagination	Brainstorming	USA	AD 1963
Simon, Herbert	The Sciences of the Artificial	Design is a study of nonphysical artificial phenomena	USA	AD 1969
	ASME Design Automation Conference	First ASME conference on design automation	USA	AD 1974
Stiny, George	Pictoral and Formal Aspects of Shape and Shape Grammars	Design can be represented as formal geometric rules	USA	AD 1975

TABLE 1.2 (CONT.). DESIGN THEORY DEVELOPMENTS IN WORLD HISTORY

Author	Publication title	Theory or development	Origin	Year
Pahl & Beitz	Engineering Design: A Systematic Approach	Systematic design as a complete process	Germany	AD 1977
Taguchi, Genichi	Jikken Keikakuho (System of Experimental Design)	Robust design	Japan	AD 1977
Suh, Nam	Axiomatic Design	Axiomatic design and design information content	USA	AD 1978
Mead, Carver, & Conway, Lynn	Introduction to VLSI Systems	Compiler theory of design synthesis, VLSI design	USA	AD 1979
Ross, Douglas		Structured Analysis and Design Technique (later called IDEF by the U.S. Department of Defense)	USA	AD 1970
Boothroyd and Dewhurst	Design for Assembly	Rules for easy assembly reduced to design principles	USA	AD 1983
Brown, D. & Chandrasekaran, B.	An Approach to Expert Systems for Mechanical Design	First expert system to do mechanical design	USA	AD 1983
Ullman, David	Proceedings, Design Theory and Methodology Conference	First ASME conference on design theory and methodology	USA	AD 1989

are at least two factors that are driving the development of design theory. The first is the need for greater corporate design efficiency. How can a group of engineers, whose members are constantly changing jobs, be made to develop new products of very high value, very quickly, at very low development cost?

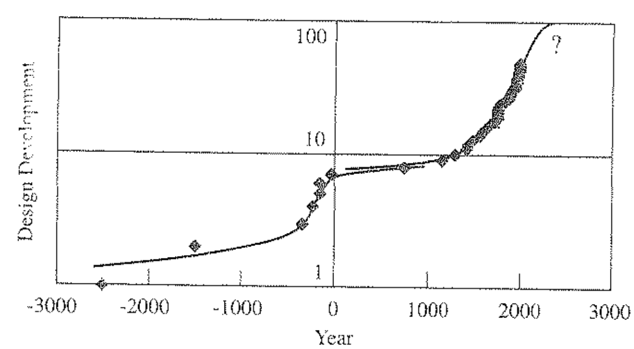

Figure 1.14.
Design theory developments over time.

Clearly, design theory can help. If a design theory is developed that is *repeatable*, for example, then increased efficiency could be gained. By repeatability we mean that the results developed are independent of the team members (at least in certain stages and methods), the process is correct when followed, and it produces a consistent result given the problem's input conditions. Some methods presented in this book do achieve this level of rigor, but others only aspire to it. The interview method of developing a list of customer needs in Chapter 4 is repeatable, but the brainstorming methods of Chapter 10 generally are not. It is an aspiration of many design researchers to develop repeatable design methods that are useful in the corporate world. On the other hand, the inventing process will never be repeatable.

Another reason for the development of design theories is the need to understand how to design with our ever-improving new technology that becomes ever more complex. For example, the explosive growth of computing capability has had a tremendous impact on engineering design. Complex static and dynamic analyses of product design concepts are now routinely considered mandatory before any gate decisions are made. Optimization of parametric values to improve the results of these analyses are also being coded and automatically solved. The fraction of design activities that are being reduced to algorithms is growing: Once a task is reduced to an algorithm, its solution can be completed or approximated in comparatively little time, and the result is guaranteed repeatable. The demand for rapid development is pushing for more such advances in algorithmic synthesis of mechanical solutions and is so driving the advancement of design theory.

Such algorithms do not remove the designers from the product development loop. Routine or contentious tasks may become less art and more repeatable. These advancements then free the design team to enjoy and focus on the challenges of design tasks, where creativity, researched knowledge, and hard work can be brought to bear.

At least one other reason for the development of design theories is the need to improve the reliability of any design process. Today, this is enforced through gates, but the typical stage-gate development process is not ideal. A gate is an artificial process constraint: Some activities may not be ready to enter the gate, while other activities may be past due for a gate. Forcing all to be ready at the same level at one point in time forces inefficiencies: Some groups relax and others burn. Similar to what has happened in manufacturing, one can expect product development to become much more instrumented and measured in order to understand where difficulties lie and where to invest.

All of these speculations simply reflect the evolutionary trends of product development as a part of the ever-competing business environment. Product development is the exciting frontline of the continually evolving battle for markets, profits, and business in our capitalist system.

VI. SUMMARY AND "GOLDEN NUGGETS"

Modern product development involves the application of objectively formulated methods that are systematically configured to permit engineers to develop products efficiently:

- Every product development process is different, as appropriate for different companys' technological and market environment.
- Students of engineering design should examine each subsequent chapter to understand the levels of detail that can be developed in each topic and at least once experience the fully detailed version before making simplifications, shortcuts, and personal versions.
- Engineers need to develop their own product development process in any business they work and must continually strive to improve it.
- Reverse engineering and redesign is a forum for learning, experimenting, and living product design. After a handful of reverse-engineering experiences, prediction of how products are executed within their "black boxes" is much more apparent. Possible alternatives and ways to execute function are also readily visualized.
- The history of methods and the science of product design are rich with tradition and wisdom, but the ink on the historical manuscript is still wet. Many more chapters are yet to be written, contemplated, and analyzed.

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