Getting It Right

R&D Methods for Science and Engineering

Peter Bock

Illustrations by Bettina Scheibe

ACADEMIC PRESS
A Harcourt Science and Technology Company
San Diego San Francisco New York Boston London Sydney Tokyo

CHAPTER 9

Overview

9.1 History of the Scientific Method

Imagine, if you will, the great philosopher Buddha (Prince Gautama Siddhartha) seated under a banyan tree in Nepal about 500 BC, surrounded by several of his devoted students. One of the more spunky students pipes up: "Master, how do we know if something is true or false? How do we know what to believe?" By way of an answer, Buddha quotes from the *Kalama Sutra,* which he has recently written:

> Do not believe in something simply because
> you have heard it.
> Do not believe in traditions simply because
> they have been handed down for many generations.
> Do not believe in something simply because
> it is spoken and rumored by many.
> Do not believe in something simply because
> it is found in your religious books.
> Do not believe in something simply on the
> authority of your teachers and elders.
> But after careful observation and rigorous analysis,
> when you find that something agrees with reason,
> and is conducive to the good and benefit of one and all,
> then accept it and live up to it.

It is rumored that the same student, on hearing this, responded: "So then, Master, does this mean that we should not necessarily believe this statement of yours either?" It is not known how Buddha reacted to this. Perhaps he smiled and enjoyed the irony with his student. Perhaps he banished the student to a corner facing the wall. It was a long time ago.

This statement by Buddha is the earliest extant example of a scholar's attempt to codify the process of scientific investigation. In addition to admonishing against accepting knowledge as a matter of faith or loyalty or popularity, he put his finger on a couple of important guiding principles for a reliable process of knowledge acquisition.

First, he suggests the task begin with a clear understanding of the problem that motivates the task. While this may seem an obvious place to start, his emphasis on "careful" observation and "rigorous" analysis implies that this should be a very thorough process, resulting in a precise statement of the objectives of the task and governed by a set of propositions that tightly constrain the form and method of any proposed solution. If the CEO of Boeing asks his engineers to design a new high-payload aircraft, a careful investigation of practical constraints, as well as a rigorous review of the state-of-the-art, will probably rule out a powerful catapult that flings a large load of anesthetized passengers from Paris to London.

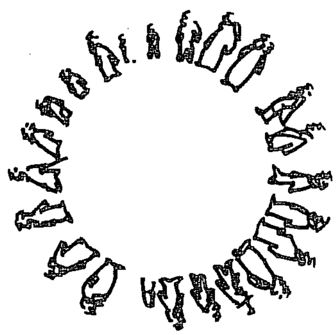
Second, Buddha suggests that this painstaking process of analysis be followed by a search for a solution to the problem that fulfills the need. The only method proposed for this search is "reason," implying that process of intellectual deduction is sufficient unto the task; think about a problem long enough and deeply enough, and a reasonable answer, if one exists, will come to you. This is where the modern Scientific Method departs radically from the seminal model offered by Buddha. In classical times, the deductive constraint was quite natural; the *metaphysical* questions that the philosophers were pondering did not lend themselves well to an empirical approach, which requires that experiments be run and results be gathered and reduced to a conclusion. It was (and still is) extremely difficult to run experiments on the transcendental nature of existence. However, as the centuries progressed and the mysteries of the behavior of the *physical* universe began to capture the attention of philosophers and their intellectual progeny (scientists and engineers), experiments became possible, and much could be learned from trying solutions in the laboratory before developing them for application in the real world.

Finally, Buddha suggests that all proposed answers be validated based on the common advantage they can provide: "conducive to the good and benefit of one and all." Again, such egalitarian metrics do not survive well outside the metaphysical domain where all humans presumably share the same spiritual fate. Today, the "bottom line" is usually much more secular: "conducive to the good and benefit of the customers," or perhaps even more cynically: "conducive to the good and benefit of the shareholders." In spiritual matters, Buddha believed we are all equal shareholders. In today's crass and commercial world, the watchword is *caveat emptor.*

In the short quotation from Buddha, he does not suggest that validation include any kind of intellectual peer review of the task results and conclusions.

However, from his complete works we know that he encouraged frequent and open discussion of new ideas among his students and disciples, subjecting the ideas to healthy criticism and cross fertilization. This part of the validation process is a mainstay of the modern Scientific Method. Perhaps peer review seemed so obvious to Buddha, being so much a part of his everyday activities, that it did not warrant any special mention in his quotation. Ironically, it is this essential process of peer review that was totally missing from the evolution of the Scientific Method in Europe until the end of the Renaissance. Even to this day, many researchers stop their tasks short of this critical final phase. The reasons for this omission, now and in the past, are manifold and often rather self-serving.

Even the great classical Greek and Roman philosophers who followed closely on the intellectual heels of Buddha, albeit on the other side of the world and without any knowledge of his work, had little to say about the *process* of knowledge acquisition. They, too, were more concerned with the *nature and definition* of truth, rather than how to acquire it. They, too, were preoccupied with deductive rationalism, building an archive of philosophical knowledge on a foundation of axioms and definitions, for which, once again, the only reasonable platform for validation was intellectual contemplation and argumentation among a small group of disciples in close contact with each other. In all fairness, beyond their immediate working groups, little communication was possible, but such intellectual inbreeding stifled innovation.



Only a few sensors for experimentation were available to the classical scholars, mainly precision instruments for measuring length. Greek mathematicians proved many fundamental theorems in geometry and mathematics that could be tested and validated empirically with these instruments. Some even attempted to use these instruments to measure the positions and deduce the motions of the heavenly bodies, but only with marginal success. The Romans were less interested in such far-flung ideas, but achieved significant Earth-bound innovations in the fields of architecture, agriculture, and civil engineering, building massive and efficient transportation systems, including highways and aqueducts. However, despite these achievements, the Greeks and Romans gave little thought to understanding and codifying the *process* of scientific investigation.

With the decline of the Greek civilization, the advent of Christianity, and the fall of Rome, almost all intellectual thought in Europe ceased. The inquisitive nature of science was firmly shackled to the chains of religious dogma. Any intellectual thought that was not literally consistent with the text of the New and

Old Testaments, the axiomatic source of all fundamental truth, was proscribed and severely punished. Literacy in Europe dropped to almost zero while the feudal barons divided and redivided the continent and hacked each other to death in the name of religion under the righteous eye of the Church. No new intellectual ideas emerged from the Dark Ages. Almost a thousand years was lost to the epistemological maturation of the human species.

And then, as described in Chapter 5 (An Epistemological Journey), the Western world began to pull out of its slump. Trade routes were established to the East, and ships began to venture farther from the European continent. With the invention of the printing press, the curse of intellectual sterility was broken, and the exchange of information exploded. Shortly after this world-shattering invention, Phillippus Aureolus Theophrastus Bombastus von Hohenheim (1493–1541) was born in Switzerland. Wisely adopting the nickname Paracelsus, this highly intelligent and wild character divided his life between medicine and debauchery. Traveling all over Europe and the Middle East, he learned everything there was to know about classical medicine and alchemy, and ended up throwing it all out of the window. He was contemptuous of the reliance of physicians on the precepts of classical alchemy that had survived the Dark Ages in musty books, which were proclaimed to contain the inspired and unimpeachable wisdom of the Golden Age. Instead, Paracelsus insisted that science must begin with a deep and clear understanding of the problem domain, followed by an hypothesis about a possible solution that must be tested impartially under carefully controlled conditions. Only then could knowledge be accepted as valid. His perpetual challenge to the classical academicians and their irrefutable classical rules, coupled with his wild life style, could have easily marked him as a heretic in those dangerous days of the Holy Inquisition, and he and his ideas were regarded with much suspicion in Catholic Europe. However, in Northern Europe under the fortunate protection of the leaders of the Protestant Reformation, his profound genius, both in knowledge and method, prevailed, and he was eventually acknowledged as a brilliant diagnostician, a brand new specialty in the field of medicine. As an example of his rigorous application of empirical research methods, Paracelsus discovered a cure for syphilis in 1527.

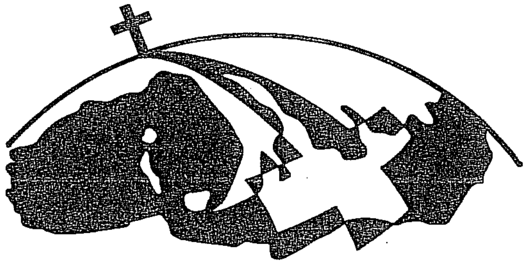
The inductive genie was out of the bottle. Scholars were abandoning the classical traditions that could not be validated, and seeking new ways to understand the behavior of the universe based on the examination and support of empirical evidence. And their findings were being printed, published, and disseminated throughout Europe. Three scientists in particular were about to merge these lessons into a single guiding principle for the conduct of research and development in science and engineering.

In England, Francis Bacon (1561–1626) not only encouraged observation and experimentation with many cases before arriving at any conclusion, but also recognized the critical importance of noting the *failures* of a theory as well as the successes. This set the ground rules for explicitly formulating and stating all governing propositions, as well as testing the proposed solution under conditions that intentionally drive it to failure.

In France, profoundly impatient with the arcane presumptive propositions that were the ironclad foundation of medieval scholasticism, René Descartes (1596–1650) argued vehemently that the process of intellectual reasoning must be founded on one, and only one, fundamental axiom, namely the acknowledgement of one's own consciousness (*cogito, ergo sum; je pense, donc je suis;* I think, therefore I am.) Everything else must derive from that, either deductively or inductively. His principles were published in 1637 in his controversial book *Discourse on the Method for Reasoning Correctly and Searching for Truth in the Sciences.* In the appendices to this book, obeying his own strictures, he presented the method of formal mathematical induction, derived the basic principles of analytic geometry from fundamental principles, and made major contributions to the field of optics. The book is a *tour de force* in research methodology.

But the real hero was Galileo Galilei (1564–1642). Unlike Francis Bacon and René Descartes, Galileo was one of the first scientists in the Scientific Revolution to conduct experiments using *sensors* to gather empirical data, such as the thermometer, timing mechanisms, and the telescope. With the telescope Galileo was able to acquire direct observational evidence to support the theories of the Polish astronomer Nicolaus Copernicus, who had hypothesized a century earlier that the Earth revolved around the Sun, not the other way around. The Copernican theory had been repeatedly rejected outright by the Catholic Church as counter to classical teachings and the Holy Scriptures. But now for the first time, the Church could no longer simply attribute the idea to the misguided ravings of heretics; now there was direct evidence that was difficult to ignore. Something had to be done. In 1633, the Office of the Holy Inquisition arrested Galileo and tried him for heresy. Their case was so precarious that they had to forge false evidence and show Galileo the instruments of torture to intimidate him into recanting, which he did.

Galileo, who had martyred himself in defense of the hypothesis of a dead man, was sentenced to spend the remainder of his life under house arrest and forbidden from publishing and interacting with his peers. He died penniless and blind in 1642, still a prisoner in his own house. He was lucky they didn't burn him at the stake. The immediate effect of Galileo's trial and conviction was to put a complete stop to all meaningful scientific inquiry in the Roman Catholic countries around the Mediterranean, and the Scientific Revolution shifted its focus to Northern Europe and nascent America once and for all.



Galileo's real crime was not that he had gathered evidence that obviated the Earth-centered universe; most intellectuals (and ship captains) of the time had already come around to the Sun-centered perspective, which made so much sense. Galileo's real crime was that he had *published* this evidence (*Dialogue Concerning the Two Chief World Systems,* 1632) in direct disobedience of the Pope (Urban VIII, Maffeo Barberini). He did so because he fervently believed that this was the final and essential phase in the process of scientific investigation: validate your results by presenting them to your peers for critical review. This idea was entirely new. Not only had this been largely impossible before the advent of the printing press, but it also requires a degree of intellectual courage and honesty that puts a strain on the most honorable of scientists. It is not easy to present your new ideas to your peers, inviting them to shoot down your methods and results with all the intellectual ammunition they can muster. Moreover, these peers are sometimes your intellectual (and perhaps personal) adversaries who are actively gunning for you, vying for the same meager sources of funding, and busy positioning themselves for maximum leverage with a meager group of patrons. In this respect, things are not much different today.

Galileo put the final piece of the modern Scientific Method in place. Yes, observe and understand. Yes, hypothesize. Yes, run the experiment and measure performance. But when all is said and done, your own conclusions are *not enough.* You must *actively* seek critical reviews of your work from others working in your field. *Your peers* must be the final arbiters, or you must show just cause why their criticism should be ignored. To validate the conclusions of science or engineering tasks, they must survive the scrutiny of your peers. One can restate this requirement as a kind of meta-null-hypothesis: successful **peer review** must reject the assertion that the conclusions of a task are inconclusive or incorrect.

Needless to say, this final phase of the modern Scientific Method has been a thorn in the sides of many scientists and engineers, past and present. It seems to make the whole process vulnerable to political and personal pressures. But with sufficient care and oversight, peer review compares very favorably with the alternative — no peer review — which invites unbridled self-deception.

9.2 The Modern Scientific Method

The historical process just described did not cease with Galileo; that was merely a moment of profound insight, a critical point in the Scientific Revolution. The subsequent influences of many great thinkers over the centuries, including Johannes

Kepler (1571–1630), Joachim Jungius (1587–1657), Johann Baptista van Helmont (1579–1644), Marin Mersenne (1588–1648), David Hume (1711–1776), Johann Wolfgang von Goethe (1749–1832), Thomas Edison (1847–1931), Bertrand Russell (1872–1970), Karl Popper (1902–1994), Peter Medawar (1915–1987), and Thomas Kuhn (1922–) have refined the concept continually as new demands were placed on science and engineering. The modern Scientific Method focuses on the formulation of hypotheses that can be rejected either in closed form or by experimentation, dubbed the *hypothetico-deductive method* by Karl Popper and Peter Medawar. This method argues that no hypothesis can ever be completely proved, but it can be disproved or rejected. Alternatively, often it can be adapted and modified so that it gradually converges more and more closely to the truth. As Peter Medawar asserts: "A scientist is a searcher after truth, but complete certainty is beyond his reach."

This book does not seek to model the way in which successful scientists and engineers think and work. Rather, it attempts to synthesize a hybrid of historical lessons, philosophical principles, and practical constraints into a consistent and comprehensive framework of knowledge and processes that may be applied to a wide variety of research and development tasks. The proposed hybrid is introduced by the following definition of the modern Scientific Method:

> **Definition 9.1** **The Scientific Method** comprises four sequential phases — Analysis, Hypothesis, Synthesis, and Validation — which are applied to a task iteratively and recursively to achieve the objective of the task.

Figure 9.1 presents a list of the major steps of each phase of the Scientific Method for both research and development tasks. Each step is a subtask of its parent phase, although its name in the task plan is often replaced by something more relevant and specific to the actual project. For example, for a theoretical research task, the step Conduct Experiments might be more properly called Check Derived Equation. In addition, when task names are used as section headers in a project report, they are often converted from imperative phrases to substantive phrases. For example, the section describing the step Solicit Peer Review might be titled Evaluation by Oversight Committee or, in the case of a doctoral research project, Dissertation Defense.

The next four chapters address the various problems and issues that arise in each phase during the planning and conduct of a research or development task. The remainder of this chapter presents a brief overview of the four phases and their internal steps by way of an introduction to the overall strategy of the modern Scientific Method.

The purpose of the Analysis Phase is to gain a clear and comprehensive understanding of the task at hand, to establish many of the governing propositions that constrain the ways in which the task and its descendant tasks may be accomplished, and ultimately to formulate a single specific and reasonable objective for the task, consistent with the imposed constraints. This process is a kind of

The Scientific Method

The iteration of four recursive phases for
the planning, conduct, and stepwise refinement
of a research or development task

Analysis	Describe Problem Set Performance Criteria Investigate Related Work State Objective
Hypothesis	Specify Solution Set Goals Define Factors Postulate Performance Metrics
Synthesis	Implement Solution Design Experiments Conduct Experiments Reduce Results
Validation	Compute Performance Draw Conclusions Prepare Documentation Solicit Peer Review

Figure 9.1 The four phases of the Scientific Method and their internal steps

"intellectual reconnaissance," during which the task team observes and organizes the details of the problem landscape in preparation for the selection of an effective solution to the problem in the Hypothesis Phase that follows. In many ways, the Analysis Phase functions like a funnel. A description of the problem is poured in the top and is progressively constrained by the imposition of practical requirements and related knowledge, so that a realistic and feasible objective for the task finally emerges at the bottom of the funnel. What begins as a broad perspective on the problem is systematically focused down to a single realistic and highly specific task objective. Chapter 10 (Analysis) discusses the Analysis Phase in detail.

Once the task objective has been firmly established, the Hypothesis Phase begins. The purpose of the Hypothesis Phase is to specify a detailed and comprehensive solution to the problem, to assert what is expected from that solution as a set of goals, and to define what factors will be varied to measure how well the task objective is achieved based on a set of postulated performance metrics. The solution can employ existing methods or new methods, or some combination of the two. Chapter 11 (Hypothesis) discusses the Hypothesis Phase in detail.

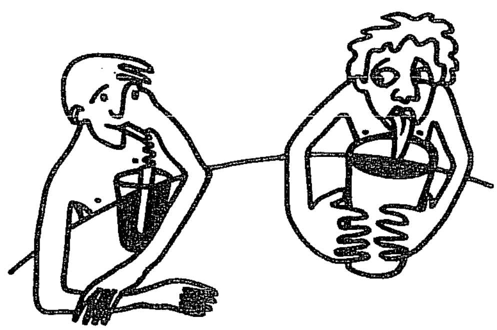
In the Synthesis Phase, the implementation of the solution specified in the Hypothesis Phase takes place. Following a rigorous experiment design that imposes the constraints of the governing propositions and factors, the implemented solution is tested through experimentation, and the results are reduced to the form necessary for the computation of the performance metrics. Bear in mind that even highly theoretical research must employ some experimentation, even if only to confirm the validity of a computation or a mathematical result derived in closed form. Chapter 12 (Synthesis) discusses the Synthesis Phase in detail.

In the Validation Phase, the performance is computed from the reduced results of the experiments using the metrics postulated in the Hypothesis Phase. Based on these performance values, the appropriate conclusions are drawn, stating whether or not and to what extent the task objective has been achieved. Finally, complete and comprehensive documentation for the entire task is prepared and submitted for critical peer review. Chapter 13 (Validation) discusses the Validation Phase in detail.

That's all there is to it: analysis; hypothesis; synthesis; and validation, and you're done. However, as you might have guessed, in reality it is never quite that simple. The devil, as they say, is in the details.

9.2.1 ITERATIVE EXECUTION

It would be naive to imagine that a task can be successfully accomplished with just one pass through the four phases of the Scientific Method. Even the simplest tasks often require several attempts to achieve the objective. For example, as you reach over to pick up a glass of lemonade from the table, you notice belatedly that the surface of the glass is covered with a thin film of condensation. Because this will probably make the glass slippery, you change your tactics for taking hold of it. Once the glass is firmly in your grasp, trying to lift it reveals that it is stuck to the table, and you change tactics again. Finally, as you lift the glass you observe that it is very full and reduce the speed of movement to your mouth. Life is full of surprises, and so is R&D.



For this reason the four phases of the Scientific Method are specifically designed to be performed iteratively, using stepwise refinement for any or all steps of the phases until the objective is achieved or the task is abandoned. The decision to return to an earlier step to revise some aspect of the task plan (or to abandon the task) can be made at any step in any phase of the process. The most common decision point is either at the end of the Synthesis Phase, when the results indicate that the task method was not successful, or at the end of the Validation Phase when the conclusions do not survive peer review. What follows are some typical actions that may be taken to attempt to recover from such failures, listed approximately in increasing order of the cost of the remedial action, *i.e.*, the number of steps that must be repeated:

- Return to the second step of the Synthesis Phase to refine the experiment design;
- Return to the second step of the Hypothesis Phase to modify the hypotheses or goals;
- Return to the first step of the Hypothesis Phase to modify the proposed solution; and
- Return to the second step of the Analysis Phase to loosen some performance criteria.

Each iteration incurs an additional cost in both time and money. Thus, each iteration following a failure to achieve the task objective should be preceded by a decision whether to continue to pursue the task objective or to abandon the entire task as a lost cause. If another iteration of the task will incur a large and unexpected cost, management will probably want to be involved in this decision to try to avoid a violation of Gresham's Law, which admonishes against throwing good money after bad.

Although abandoning a task is usually an unattractive and discouraging conclusion, task failure is a very common occurrence; the vast majority of research and development tasks are unsuccessful.[1] It is important, therefore, to find out as quickly as possible whether a task is likely to be successful or not. A good way to do this is to mount a series of preliminary **feasibility pilot** tasks (see Chapter 3).

Feasibility pilots (also called **QD pilots**, for Quick-and-Dirty) are simplified and rather informal investigations designed to quickly and inexpensively explore the feasibility of a proposed solution or an experiment design. Such pilots are not usually reported in the final project documentation; no one is very interested in a chronicle of the failures that preceded success. However, no matter how quick-and-dirty a QD pilot is, it is extremely important for the task team members to *record the details of every QD pilot in their research notebooks.* It is so very easy to lose track of what has been investigated and what has not, especially when the QD pilot tasks are being performed quickly, one after another, with little formal planning and management oversight. The heady excitement of converging on a promising solution or the frustration of repeated failures in a series of QD pilots can easily distract the researcher from keeping careful records in the interest of "saving time," which often seems to be slipping away uncontrollably. Almost inevitably, this lack of a detailed audit trail for the QD pilots leads to unnecessarily repeated trials, resulting in a lot of frustration and wasted time, simply because the researcher lost track of the thread of the search by trying to keep it all in the head: "What in blazes did I do yesterday that yielded those really good results?!"

[1]Of course, such failures are not usually reported in the literature. I have always thought it would be a good idea to publish a *Journal of Unsuccessful Research* (with anonymous authorship, of course) to save researchers from unnecessary expense and anguish by informing them about things that just don't work, *i.e.*, good idea, no cigar.

or "This value didn't work yesterday when I tried it! Now it does! What's going on?" Every one of us has experienced this kind of frustration, and it is a terrible waste of time and energy that can be largely avoided through rigorous and comprehensive record keeping. It is just a matter of discipline. Wax on, wax off.

QD pilots can be used at every step of *every phase of the task,* not just when exploring the feasibility of a proposed solution. For example, during the Related Work step of the Analysis Phase, a quick bibliographical search on the Internet can provide a survey of methods that have been used in the past to solve the research problem, which may profoundly affect the funding and time required to achieve the task objective. Similarly, a series of "dress rehearsals" with a small number of subjects (perhaps colleagues or team members) will help to debug a complex experiment protocol, even though these pilot subjects may not be demographically equivalent to the subjects in the cohort to be used for the "real" experiments. In the following chapters on the four phases of the Scientific Method, there are specific suggestions for where and how a QD pilot might be useful to estimate the feasibility of proposed task components or to identify potential problems and obstacles.

It is extremely important to remember that the results of feasibility pilots are *not* conclusive. Once a feasibility pilot has yielded a potentially useful result, a *formal* task must be rigorously designed and executed to confirm and validate this informal result.

> **TIP 12**
> Feasibility or QD pilots are useful for exploring the feasibility of proposed task components. Every QD pilot, although perhaps only minimally planned and not usually reported in the final project documentation, *must* be fully recorded in the cognizant team members' research notebooks. Once a QD pilot has yielded a potentially useful result, it *must* be confirmed and validated by planning and executing a formal task.

It is important to remember that planning is an integral part of every project, not a separate activity that is simply tolerated as a kind of unfortunate overhead. Very often both managers and project team members are impatient with planning, anxious to "just get on with it." Because these two groups generally agree on this, there is a strong mutual tendency to minimize or even skip planning efforts, resulting in a large increase in the overall task time. By the same token, however, it is clearly important to minimize the *overall* task time to avoid wasting unnecessary time and effort. The ever-present problem, then, is how to minimize the overall task time, while also ensuring that meaningful results are obtained as quickly and efficiently as possible.

What is the appropriate amount of time that should be spent *planning* a task, as opposed to *executing* it? Clearly, the answer to this question depends on a great many factors that are very difficult to codify: the difficulty and scope of the task, the experience of the task team, the resources available for the task, and so forth. Nonetheless, we can attempt to address this question by constructing a *very* simple model for planning and executing a task to get a general idea of the optimal task planning time.

This model rests on two major simplifying presumptive propositions. First, we postulate that the necessary number of iterations for stepwise refinement to complete a task is inversely proportional to the *task planning time,* expressed as percent of the *ideal task time* (*i.e.,* if the task were executed without any errors or delays whatsoever). Under this postulate, as the amount of planning time approaches zero, the number of necessary iterations approaches infinity, *i.e.,* if no time is spent for planning, the task process is a random walk. At the opposite extreme, if an infinite amount of time is spent for planning, then the number of necessary *repeats* of the process approaches zero, *i.e.,* the task is successfully accomplished after one pass (no repeats), but the total task time is still infinite because the planning time is infinite (one just never gets around to executing it). Second, we assume that on the average each iteration repeats only half of the ideal task time. Figure 9.2 presents the behavior of this simple model, which has a saddlepoint where the planning time minimizes the overall task time.

The saddlepoint in the curve in Figure 9.2 suggests that the appropriate amount of planning time is about 70% of the ideal task time. At this point, the

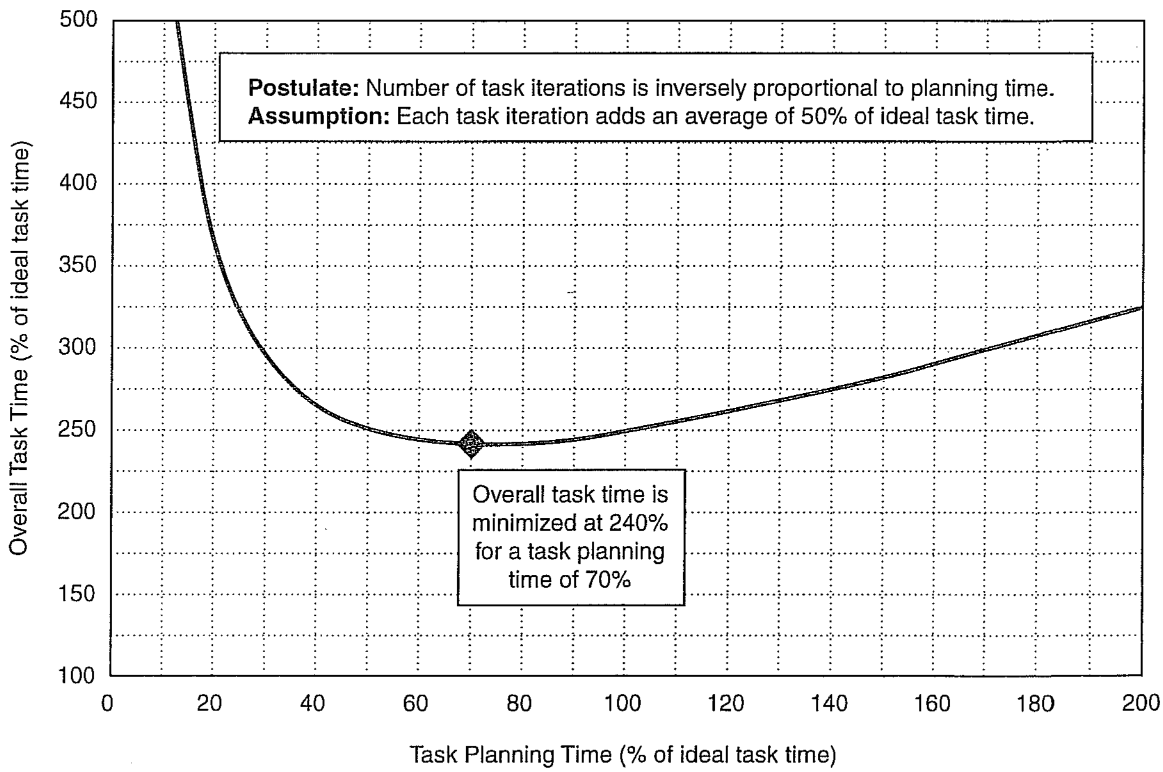


Figure 9.2 A simple model of the relationship between overall task time and planning time

overall task time, including planning time, is about 240% of the ideal task time, meaning that every individual step of the task must be performed an average of 2.4 times. For example, if the expected ideal task time were one person-year, this would suggest that the planning time should be about 8 person-months (70% of one person-year), and that the overall task time, including planning, would be about 2.4 person-years (240% of one person-year).

Having said that, please note that it is not appropriate to use Figure 9.2 to obtain actual numbers for the task time ratios. Instead, the curve should be regarded as a very simple abstraction of the general relationship between task planning time and overall task time. At best, one might consider the following conclusions:

- As the task planning time is *decreased* from the saddlepoint, the overall task time increases very quickly, resulting in excessive and wasteful iteration.
- As the task planning time is *increased* from the saddlepoint, the overall task time increases rather slowly.
- The two preceding observations suggest that saddlepoint in the overall task time should be interpreted as corresponding to a *minimum* planning time, rather than an optimum.

TIP 13
In general, too little planning time incurs much heavier penalties in overall task time than too much planning time.

A short summary of the concepts presented in this chapter so far is probably useful at this point. Iterative execution of the Scientific Method allows the orderly stepwise refinement of a task plan and its components. Large strategic changes, usually driven by partial or complete failures of one or more task components, must be accompanied by explicit and formal modifications of the task plan, which often require the concurrence of project management. Small tactical adjustments can be made unilaterally "on the fly," which, although perhaps not reported in the final project documentation, must be thoroughly and clearly documented in the research notebooks of the team members. QD pilots are useful for exploring the performance of proposed task components and for identifying potential obstacles and problems in the task components with minimal expense. Finally, planning is an integral part of any task that takes place at the beginning and *throughout* the task, especially when iterative stepwise refinement takes place. In general, insufficient planning causes a much higher risk of increasing overall task time than excessive planning, suggesting that the task personnel should engage in more, rather than less planning.

9.2.2 RECURSIVE EXECUTION

As was explained in Chapter 3 (The Project Hierarchy), every research or development project comprises a hierarchy of tasks. Theoretically, a project hierarchy could consist of a single task occupying a single level. However, just as it is naive to assume that a task can be accomplished without iterative stepwise refinement, it is equally unlikely that a complete project plan would have just a single level in its task hierarchy. Even the simplest project is more complicated than that. In fact, from the structure of the Scientific Method just presented, we now know that every project (or task) can be quite properly decomposed into four sequential groups of tasks, each representing one of the four phases of the Scientific Method: Analysis; Hypothesis; Synthesis; and Validation. Thus, every project can be represented with at least two levels in its hierarchy, as illustrated in Figure 9.3. The tasks are grouped by phase, as indicated by the labels in the shaded areas.

As explained in Chapter 3 (The Project Hierarchy), each of the second-level tasks shown in Figure 9.3 is a project in its own right. Therefore, each of these second-level tasks may in turn be decomposed into four groups of subtasks at the third level, one for each of the four sequential phases of the Scientific Method, as shown in Figure 9.4. In the interest of visual clarity, only the decomposition of the second-level Synthesis Task 1.5 is shown, even though several of the tasks at the second level are actually broken down, as indicated by the vertical ellipses. The fact that there are no ellipses below Tasks 1.3, 1.4, and 1.7 in the second level simply means that no further planning detail was required (or at least specified) for these tasks at lower levels.

And, of course, this recursive process of **hierarchical task decomposition** may be repeated indefinitely. Additional levels in the hierarchy may be added until sufficient layers of detail of the project plan have been fleshed out. Some branches in the project task tree may need more levels than others, depending on how much low-level detail is required for each particular task.

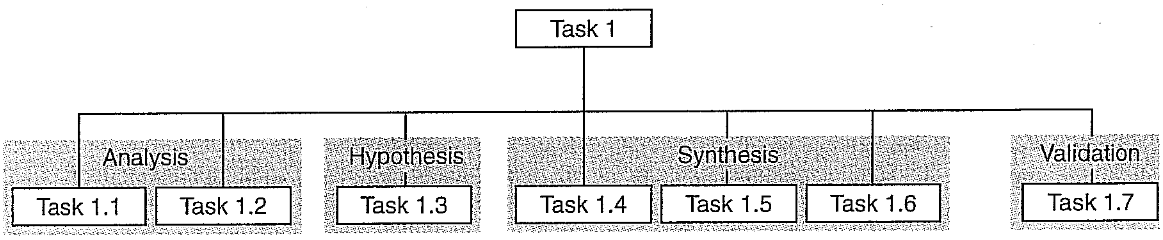


Figure 9.3 Illustration of a two-level project hierarchy

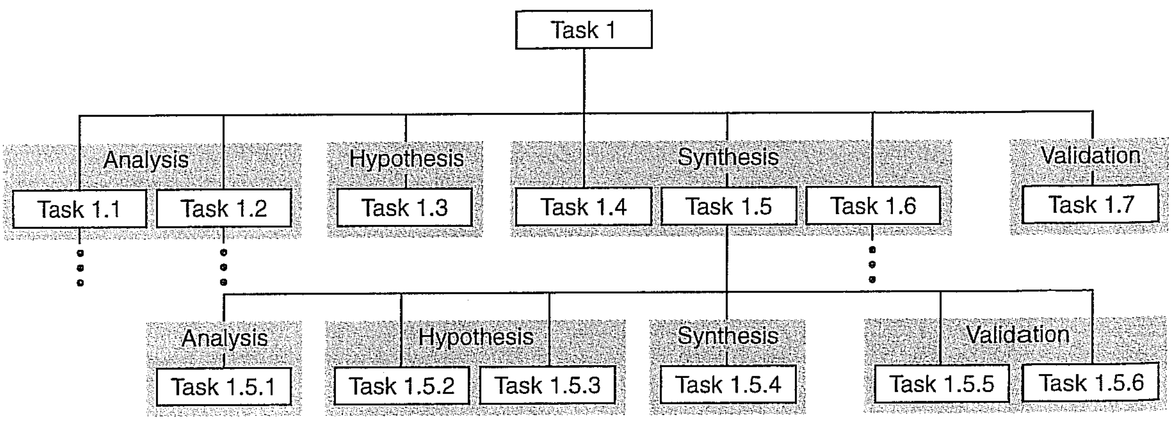
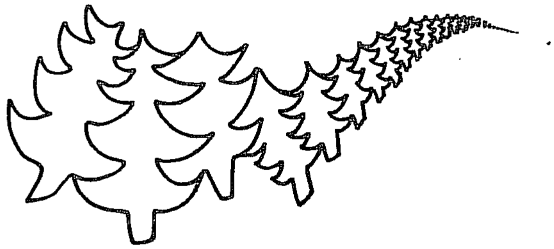


Figure 9.4 Illustration of a three-level project hierarchy (partial)



What does it mean to include several tasks within the same phase, *i.e.,* when several tasks occupy the same shaded area on the project task trees in Figures 9.3 and 9.4? It means that this phase requires more than one descendant task to achieve the objective of the parent task. This is not surprising, because we have already defined four steps, or subtasks, for each of the four phases, as shown in Figure 9.1. For example, the two tasks in the Analysis Phase group in Figure 9.3 might well correspond to the steps Describe Problem and Set Performance Criteria. When these two tasks have been successfully completed, their results contribute to the successful accomplishment of the entire Analysis Phase for parent Task 1. The remaining steps in the Analysis Phase of Task 1 are not broken out, implying (hypothetically) that they are either included in the two descendant tasks that *are* broken out, or are handled directly by the parent Task 1.

Likewise, two of the tasks in the Hypothesis Phase group in Figure 9.4 (Tasks 1.52 and 1.53) might correspond to the steps Specify Solution and Postulate Performance Metrics. Once again, the other two steps in the Hypothesis Phase (Hypothesis and Goals, and Factors) are not broken out, implying that they are either included in the descendant tasks that *are* broken out, or are handled directly by parent Task 1.5.

It is important to emphasize once again that every time a subtask is spawned, it reinvokes the *entire* Scientific Method, from Analysis to Validation. Having said that, in general the deeper the subtask in the project task tree, the briefer its Analysis Phase, because much of the required information has already been included in the Analysis Phase of the higher-level tasks. Thus, the Analysis Phase of a subtask might well be limited to a few sentences or a short paragraph.

The Hypothesis, Synthesis, and Validation Phases of the subtask, however, are often *more* detailed than those of the high-level tasks, because the closer you get to the terminal subtask, the more actual work is being planned and executed. For example, one of Clyde Tombaugh's very-low-level subtasks for his project ***Find New Planet*** was probably something like ***Set Up Telescope Camera***, which almost certainly involved a complex task method that had to be planned in great detail and executed meticulously to ensure efficient, accurate, and consistent use of the equipment at the Lowell Observatory, even though the high-level astrophysical analysis had been accomplished long before.

Even though the task descriptions for the internal steps of a phase are often subsumed by the parent task because their task descriptions are brief and self evident, it is very easy for the number of pages required to *document* a complete project task tree (or project milestone chart) to become very, very large. Fortunately, the very nature of top-down design allows a project task tree to be cut down to an arbitrarily small tree, which represents either a small piece of the project with extremely *high* precision, a large piece of the project with very *low* precision, or anywhere in between. All are useful and accurate representations. Even so, the planning documents can quickly grow into an immense stack of papers that, taken together, provide the necessary detail of the project plan for all its component tasks at many different levels of precision. This is unavoidable, and, in fact, absolutely necessary in the end; after all, it takes an immense stack of planning documents to include all the necessary specifications and blueprints for constructing a hydroelectric power plant or a commercial jet aircraft.

To illustrate the evolution of a project plan based on the Scientific Method supported by its knowledge propositions, excerpts from a case study will be presented from time to time during the next four chapters: ***Measure Character-Recognition Performance***. This case study is an abbreviated version of the final report for an actual industrial research project conducted several years ago to measure the ability of inspectors to accurately recognize the numbers and letters on video images of automobile license plates. Only short and often incomplete textual descriptions are included in the excerpts of the case study; ellipses (. . .) at the end of sentences or paragraphs are used to indicate incomplete text, which was much longer in the original project documentation. This compromise, however, does demonstrate that the information presented using the proposed methodology, albeit in abbreviated form, can be largely self explanatory.[2]

The project task tree in Figure 9.5 is a high-level project task tree of the major tasks for the case study. Although Figure 9.5 represents the final version of the project task tree, it evolved gradually from the first version, which was created on the first day of the project. When a research or development project is initiated, it is appropriate to construct an initial project task tree and a milestone chart as soon as possible. Of course, this initial plan can only be a very sketchy and approximate estimate of the eventual task structure and schedule, and the final project task tree and milestone charts will bear little resemblance to it. But all project plans evolve, and it is important to get something down on paper as soon as possible to put the project into some kind of perspective and to begin to assign tasks and resources.

TIP 14

Because the project task tree and milestone chart present an overview of every step within every phase of the Scientific Method for a project, it is particularly useful as one of the primary planning documents, a current copy of which should always be in the hands of every team member.

---

[2]All of the bibliographical citations in the tables and figures that describe the case study project *Measure Character-Recognition Performance* have been fictionalized to disguise the identity of the company that performed this research project. The important details of the project, however, are factual. Also note that the numbering scheme for the figures and tables within the illustrations for this case study is disjoint from the numbering scheme for the figures and tables of the book itself. The figure and table numbers are prefixed with CS to indicate that they belong to the case study.

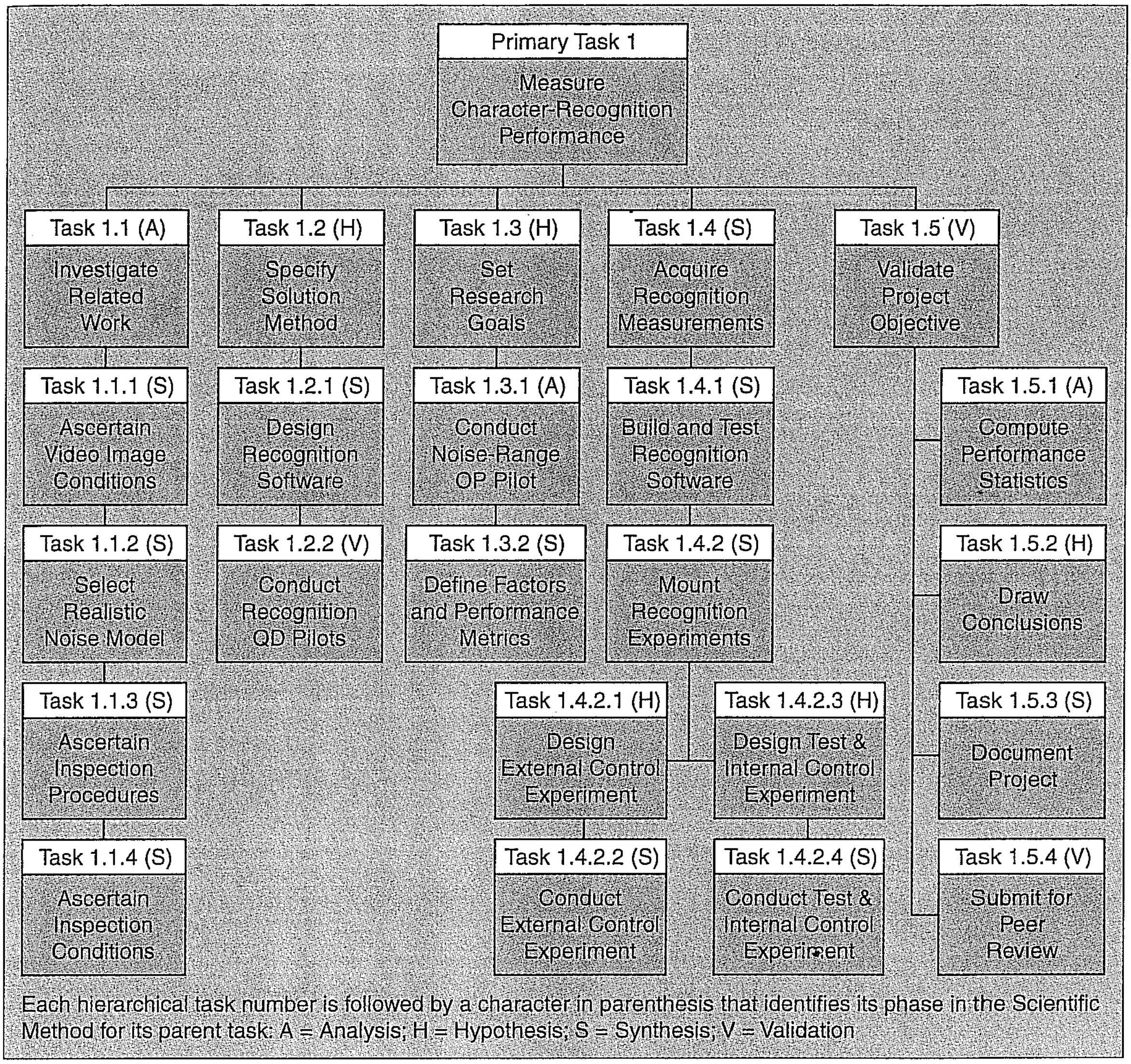


Figure 9.5 Task tree for Project ***Measure Character-Recognition Performance***

Not every task that was undertaken in the project is listed explicitly in Figure 9.5. Many phases are not shown, only a few of the steps within each phase are listed at each level, and only three levels in the hierarchy are shown. Clearly, then, this is a high-level description of the project, and the omitted phases and steps are subsumed either by the parent task or by another task at the same level. In point of fact, during the course of the project the members of the project team constructed many additional task trees, which decomposed the tasks listed in Figure 9.5 into hierarchies of subtasks that were important for each member's specific responsibilities.

As mentioned in Section 3.2, the **milestone chart** is another useful way of representing a project plan to include scheduling information. The team for the project *Measure Character-Recognition Performance* constructed milestone charts for the high-level task trees. At the low levels in the task hierarchy, however, milestone charts are often omitted because the scheduling information is too inaccurate and volatile at the corresponding time precision. After all, the times for events on a milestone chart for the homeowner's subtask *Remove Screws* would have to be expressed in units of minutes, which would have been a bit silly. On the other hand, rather ironically, it was during this particular subtask that the entire project failed, partly as a result of poor scheduling!

Even though some subtasks are not explicitly scheduled and/or some subtasks are not explicitly broken out in the task tree, these subtasks *happen* and therefore need to be planned. If little or no effort is applied to planning, then either the planning process has simply been overlooked, or the task members think they can keep all of the necessary information and relationships in their heads and plan on the fly. Either way, this can be a catastrophe waiting to happen.

TIP 15

For R&D scientists and engineers: Resist the urge to "make it up as you go along." Plan the project thoroughly in advance, but allow the plan to evolve as experience and pilots reveal the flaws and potential improvements in the plan. Be prepared to give management time and cost estimates whose accuracy they can trust. If you discover you will not be able to make a deadline, notify your manager immediately; don't wait until the last moment. Understand that managers see and deal with a larger perspective than you do. Accept that the workplace is not a democracy.

TIP 16

For R&D managers: Support your scientists and engineers with the time and resources necessary to plan and stepwise refine these plans throughout the lifetimes of projects. Limit the work of each person to one or two concurrent projects. Don't steal time from project scientists and engineers for "fire drills"; hire special staff members for that purpose. Don't micromanage. Don't nickel-and-dime. Try not to burden your scientists and engineers with bureaucratic tasks; that's *your* job. If you have no choice, then explicitly acknowledge that the associated time and costs of the bureaucratic task are not a part of the ongoing project budgets, and extend all deadlines appropriately.

Making intelligent decisions about how much detail is required in a project task plan, how the steps in each of the four phases should be appropriately grouped and decomposed, and how and where the relevant governing propositions for the project should be stated depends on two issues: 1) the size and nature of the specific task and its components; and 2) a solid grasp of the purposes and functions of the four phases of the Scientific Method and their internal steps.

There is no way, of course, that this book can address the first issue, other than by example and analogy. However, the second issue is addressed squarely in the next four chapters, which present a general methodology for the planning and execution of R&D tasks based on the Scientific Method.

Exercise 9.1
Construct a set of task trees and their associated milestone charts for a project you are currently planning or undertaking.