RICHARD PAUL, ROBERT NIEWOEHNER,
AND LINDA ELDER

SECOND EDITION

THE THINKER'S GUIDE TO ENGINEERING REASONING

FOUNDATION FOR CRITICAL THINKING

Based on Critical Thinking Concepts and Principles

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Based on Critical Thinking Concepts & Tools

SECOND EDITION

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Foreword

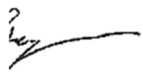
I am delighted to recommend *The Thinker's Guide to Engineering Reasoning* for engineering instructors, students, and engineers alike. This guide is a very useful addition to the arsenal of engineering education tools. I believe it fills a gap that has been largely ignored in engineering instruction. It covers an important area of competence that we so often presume students will acquire, but traditionally (and sadly) do not sufficiently address, if at all.

An isolated focus on technical skill delivery, or on one skill area, has not worked in the past, currently fails and will not meet tomorrow's needs. It is important for the field of engineering to be understood as systems of overlapping and interrelated ideas, rather than isolated and different fields of knowledge. Moreover, it is important to recognize and effectively deal with the multiple environmental, social and ethical aspects that complicate responsible engineering. Accordingly, it is time for engineering educators to realize that effective engineering instruction cannot be based in memorization or technical calculation alone. Rather, it is essential that engineering students develop the generalizable critical thinking skills and dispositions necessary for effectively and professionally reasoning through the complex engineering issues and questions they will face as engineers. The authors outline and detail these skills and dispositions quite effectively in this guide.

I am further delighted to note the level of detailed sub distinctions covered in the guide. I believe it is Dave Merrill who originally claimed that expertise is defined by the number of detailed sub-divisions clearly made and qualified. As such, the authors have proven mastery!

Growing industry dissatisfaction with deficient engineering education has led to the inception of the CDIO™ Initiative. This international design addresses engineering education reform in its broader context. Active student participation forms an integral part of this solution. While not the exclusive aim or application of this guide, its potential to compliment such institutional reforms by equipping the student to step up to the challenges of independent reasoning, is particularly beneficial.

The Thinkers Guide to Engineering Reasoning is not only a must-read publication for engineering educators, but a vital guide and career long companion for students and engineers alike.



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Introduction

Why A Thinker's Guide to Engineering Reasoning?

This thinker's guide is designed for administrators, faculty, and students. It contains the essence of engineering reasoning concepts and tools. For faculty it provides a shared concept and vocabulary. For students it is a thinking supplement to any textbook for any engineering course. Faculty can use it to design engineering instruction, assignments, and tests. Students can use it to improve their perspective in any domain of their engineering studies.

General critical thinking skills apply to all engineering disciplines. For example, engineering reasoners attempt to be clear as to the purpose at hand and the question at issue. They question information, conclusions, and points of view. They strive to be accurate, precise, and relevant. They seek to think beneath the surface, to be logical, and objective. They apply these skills to their reading and writing as well as to their speaking and listening. They apply them in professional and personal life.

When this guide is used as a supplement to the engineering textbook in multiple courses, students begin to perceive applications of engineering reasoning to many domains in their lives. In addition, if their instructors provide examples of the application of engineering thinking to life, students begin to see good thinking as a tool for improving the quality of their lives.

If you are a student using this guide, get in the habit of carrying it with you to every engineering class. Consult it frequently in analyzing and synthesizing what you are learning. Aim for deep internalization of the principles you find in it—until using them becomes second nature.

While this guide has much in common with *A Thinker's Guide to Scientific Thinking*, and engineers have much in common with scientists, engineers and scientists pursue different fundamental purposes and are engaged in distinctively different modes of inquiry. This should become apparent as you read this guide.

A Framework for Engineering Reasoning

The analysis and evaluation of our thinking as engineers requires a vocabulary of thinking and reasoning. The intellect requires a voice. The model on the facing page is not unique to engineering; indeed, its real power is its flexibility in adapting to any domain of life and thought. Other Thinkers' Guides in the Thinker's Guides library[1] apply this framework to other disciplines. Engineers and scientists are quite comfortable working within the context of conceptual models. We employ thermodynamic models, electrical models, mathematical models, computer models or even physical models fashioned from wood or clay. In this guide we apply a model or framework for thinking, an architecture whose purpose aids the analysis and evaluation of thought, through which we might improve our thought. A glance at other Thinkers' Guides reveals that only shifts of emphasis are required to apply this model to the sciences, the humanities, or the arts.

The framework depicted on the following page provides an overview of the entire guide, working from the base of the diagram up. The goal or endpoint is the development of the mature engineering thinker; therefore, that endpoint is described first with a brief discussion of the intellectual virtues as might be expressed in the practice of engineering.

Subsequently, the eight elements of thought are introduced. These are tools for the analysis of thinking in ones' own and others' thought. These elements are then exemplified and applied to analyzing texts, articles, reports, and entire engineering disciplines.

Next, the intellectual standards are introduced and exemplified. These constitute the thinker's *evaluation* tools. They are then woven together with the elements in several formats to demonstrate application of these *evaluation* standards to the *analysis* of our thinking.

Finally, the guide includes several case studies of excellent thinking and deficient thinking in engineering. It then concludes by treating a number of distinctive topics that touch on the engineering profession, such as aesthetics, ethics, and engineers' relationships with other professionals.

Using this Thinker's Guide

As with the other guides in the *Thinker's Guide* series, the content in this guide is not to be read as straight prose; it is predominantly composed of numerous examples, mostly probing questions, of a substantive critical thinking model applied to the engineering context. These examples may be used in class exercises, as reference material, or as templates for out-of-class work, which students adapt to their own courses, disciplines, and projects. A broader discussion of the approach to critical thinking used in this guide can be found in resources and articles on the website of the Foundation for Critical Thinking, www.criticalthinking.org. For deeper understanding of the basic theory of critical thinking, we especially recommend the book, *Critical Thinking: Tools for Taking Charge of Your Professional and Personal Life,* also available from the Foundation for Critical Thinking.

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1 See The Thinker's Guides Library on pp. 52-54.

Engineers concerned with good thinking routinely apply ***intellectual standards*** to the ***elements of thought*** as they seek to develop the traits of a mature engineering mind.

Intellectual Traits Essential to Engineering Reasoning

No engineer can claim perfect objectivity; engineers' work is unavoidably influenced by many variables, including their education, experiences, attitudes, beliefs, and level of intellectual arrogance.

Highly skilled engineers recognize the importance of cultivating intellectual dispositions. These attributes are essential to excellence of thought. They determine with what insight and integrity one thinks.

Intellectual humility is knowledge of ignorance, sensitivity to what you know and what you do not know. It implies being aware of your biases, prejudices, self-deceptive tendencies, and the limitations of your viewpoint and experience. Licensure as a Professional Engineer (PE) explicitly demands that engineers self-consciously restrict their professional judgments to those domains in which they are truly qualified.[2] Questions that foster intellectual humility in engineering thinking include:

- What do I really know about the technological issue I am facing?
- To what extent do my prejudices, attitudes, or experiences bias my judgment? Does my experience really qualify me to handle this issue?
- Am I quick to admit when I am dealing with a domain beyond my expertise?
- Am I open to considering novel approaches to this problem, and willing to learn and study where warranted?

Intellectual courage is the disposition to question beliefs about which you feel strongly. It includes questioning the beliefs of your culture and any subculture to which you belong, and a willingness to express your views even when they are unpopular (with management, peers, subordinates, or customers). Questions that foster intellectual courage include:

- To what extent have I analyzed the beliefs I hold which may impede my ability to think critically?
- To what extent have I demonstrated a willingness to yield my positions when sufficient evidence is presented against them?
- To what extent am I willing to stand my ground against the majority (even though people ridicule me)?

Intellectual empathy is awareness of the need to actively entertain views that differ from your own, especially those with which you strongly disagree. It entails accurately reconstructing the viewpoints and reasoning of your opponents and reasoning from premises, assumptions, and ideas other than your own. Questions that foster intellectual empathy include:

- To what extent do I listen and seek to understand others' reasoning?
- To what extent do I accurately represent viewpoints with which I disagree?
- To what extent do I accurately represent opponents' views? Would they agree?

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2 National Society of Professional Engineers. 2003. *Code of Ethics for Engineers*. www.nspe.org/ethics/codeofethics2003.pdf.

To Analyze Thinking We Must Learn to Identify and Question its Elemental Structures

Note: When we understand the structures of thought, we ask important questions implied by these structures.

A Checklist for Engineering Reasoning

1. **All engineering reasoning expresses a *purpose*.**
   - Have I distinguished my purpose from related purposes?
   - Have I checked periodically to be sure I am still on target?
   - Have I chosen realistic and achievable purposes?
2. **All engineering reasoning seeks to figure something out, to settle some *question*, solve some engineering *problem*.**
   - Have I stated the question at issue clearly and precisely?
   - Have I expressed the question in several ways to clarify its meaning and scope?
   - Have I divided the question into sub-questions?
   - Have I determined if the question has one right answer, or requires reasoning from more than one hypothesis or point of view?
3. **All engineering reasoning requires *assumptions*.**
   - Have I clearly identified my assumptions and determined whether they are justifiable?
   - Have I considered how my assumptions are shaping my point of view?
   - Have I considered which of my assumptions might be resonably questioned?
4. **All engineering reasoning is done from some perspective or *point of view*.**
   - Have I identified my specific point of view?
   - Have I considered the point of view of other stakeholders?
   - Have I striven to be fairminded in evaluating all relevant points of view?
5. **All engineering reasoning is based on *data, information*, and *evidence*.**
   - Have I validated my data sources?
   - Have I restricted my claims to those supported by the data?
   - Have I searched for data that opposes my position as well as alternative theories?
   - Have I ensured that all data used is clear, accurate, and relevant to the question at issue?
   - Have I ensured that I have gathered sufficient data?
6. **All engineering reasoning is expressed through, and shaped by, *concepts* and *theories*.**
   - Have I identified key concepts and explained them clearly?
   - Have I considered alternative concepts or alternative definitions of concepts?
   - Have I distorted ideas to fit my agenda?
7. **All engineering reasoning entails *inferences* or *interpretations* by which we draw *conclusions* and give meaning to engineering data and work.**
   - Have I inferred only what the data supports?
   - Have I checked inferences for their internal and external consistency?
   - Have I identified assumptions that led to my conclusions?
8. **All engineering reasoning leads somewhere or has *implications* and *consequences*.**
   - Have I traced the implications that follow from the data and from my reasoning?
   - Have I searched for negative as well as positive implications (technical, social, environmental, financial, ethical)?
   - Have I considered all significant implications?

The Spirit of Critical Thinking

Analyzing an Engineering Document

One important way to understand an engineering article, text or technical report, is through analysis of the structure of an author's reasoning. Once you have done this, you can then evaluate the author's reasoning using intellectual standards (see page 26). Here is a template to use:

1. The main ***purpose*** of this engineering article is ____________________.

   (State, as accurately as possible, the author's purpose for writing the document. What was the author trying to accomplish?)

2. The key ***question*** that the author is addressing is ____________________.

   (Your goal is to figure out the key question that was in the mind of the author when s/he wrote the article. In other words, what key question is addressed?)

3. The most important ***information*** in this engineering article is ____________________.

   (Identify the key information the author used [illegible] n the article to support his/her main arguments. Here you ar [illegible] experiences, and/or data the author is using to support he [illegible] s well as its sources.)

4. The main ***inferences***/conclusions in this article are ____________________.

   (Identify the most important conclusions that the author reaches and presents in the article.)

5. The key ***concepts*** we need to understand in this engineering article are ____________________.

   By these *ideas* the author means ____________________.

   (To identify these concepts, ask yourself, What are the most important ideas or theories you would have to understand in order to understand the author's line of reasoning? Then briefly elaborate what the author means by these ideas.)

Analyzing an Engineering Document (cont'd)

6. The main ***assumption***(s) underlying the author's thinking is (are) ________________________.

   [illegible] What is the author taking for granted [that might be [illegible] assumptions are generalizations that the author does not [illegible] fense in this context, and they are usually unstated. This is where the author's thinking logically begins.)

7a. If we take this line of reasoning seriously, the ***implications*** are ________________________.

   (What consequence[illegible] llow if people accept the author's line of reasoning? Here yo[illegible] ut the logical implications of the author's position. You shoul[illegible] ations the author states, but also include those the author does not state.)

7b. If we fail to take this line of reasoning seriously, the ***implications*** are ________________________.

   (What consequences are likely to follow if people ignore the author's reasoning?)

8. The main ***point(s) of view*** presented in this engineering article is (are) ________________________.

   (The main question you are trying to answer here is, What is the author looking at, and how is s/he seeing it? For example, in this guide we are looking at engineering reasoning and seeing it "as requiring intellectual discipline and the development of intellectual skills."

If you understand these structures as th[illegible] le, or technical report, you should be able t[illegible] of the author. Remember, the eight basic [illegible] here define all reasoning, regardless of d[illegible] extension, they are also the essential elements of engineering reasoning.

Two Kinds of Engineering Questions

In approaching a question, it is helpful to determine the kind of system to which it belongs. Is it a question with one definitive answer? Alternatively, does the question require us to consider competing answers or even competing approaches to either solution or conceptualization?

Questions of Procedure (established system)—Questions with an established procedure or method for finding the answer. These questions are settled by facts, by definition, or both. They are prominent in mathematics as well as the physical and biological sciences. Examples include:

- What materials do building codes require for this application?
- What is the yield strength of this material?
- How much electrical power does this equipment need?
- How hot does this fuel burn?

Questions of Judgment (conflicting systems)—Questions requiring reasoned judgment, and with more than one arguable answer. These are questions that make sense to debate, questions with better-or-worse answers (well-supported and reasoned or poorly-supported and/or poorly-reasoned answers). Here we are seeking the best answer within a range of possibilities. We evaluate answers to such questions using universal intellectual standards such as breadth, depth, logicalness, and fairness. Some of the most important engineering questions are conflicting-system questions (for example, those questions with an ethical dimension). Examples include:

- How long will this part last?
- Should the development follow a spiral or waterfall management model?
- Is the customer most concerned with cost or performance?
- How does the customer define "acceptable risk?"
- What model should be employed to reduce environment impact?

Analyzing Disciplines: Aerospace Engineering

Purpose. Aerospace Engineering develops aerial and space-based systems for defense, scientific, commercial, civil, and recreational markets and missions. General mission needs within those markets include transportation, earth and space sensing, and communications. Typically, the products are vehicles such as rockets, airplanes, missiles, satellites, and spacecraft, although the product may also include the ground support equipment, or imbedded hardware or software.

Key Question(s). What are the detailed design features of the system that best satisfy the stated mission or market requirement? How will we design, build, test, fabricate, and support aerospace vehicles?

Point of View. The conceptual mission profile typically provides the organizing framework for all design requirements and design decisions. The attempt is to define value principally from the perspective of the organizational leader who is sending the vehicle on some mission flight (and paying for the flight). Other perspectives may also be relevant: pilots, maintainers, manufacturing, and logisticians, as well as technologists (structural engineers, aerodynamicists, controls engineers, propulsion engineers, and relevant others). Politicians will likely be influential in large aerospace programs. Public opinion, concerned with ethical or environmental issues, are often relevant, and if so, must be considered.

Key Concepts. These include all those concepts associated with classical physics, with some particular emphases: Newtonian and orbital mechanics, conservation of mass, momentum and energy, low and high speed aerodynamics, material properties and lightweight structures, propulsion technologies.

Key Assumptions. Assumptions are in part shared by all scientists and engineers. One assumption is that the universe is controlled by pervasive laws that can be expressed in mathematical terms and formulas. Additionally, aerospace engineers assume that an aerospace solution will invariably entail the integration of multiple technological disciplines and the resolution of competing design tensions, including aerodynamics, astrodynamics, stability and control, propulsion, structures, and avionics. Furthermore, the aerospace system will be a system of systems, which must also fit and interface with a larger system (e.g., air cargo airplanes must fit and communicate with the air traffic control structures, missiles must fit with existing launch rails; satellites must fit on independently developed launch vehicles).

The Data or Information. Aerospace engineers employ experimental and computational data, legacy designs, regulatory requirements, market studies or mission needs statements.

Inferences, Generalizations, or Hypotheses. The conclusion of most aerospace engineering activity is a product ready for delivery to a customer.

Implications. Aerospace engineering products and services have wide-ranging implications, linked with global, national, local economics, ethics, defense, security, environmental effects such as noise and pollution, and infrastructure such as airports, any of which may impact the quality of life in communities and regions.