The Thinker's Guide to

Engineering Reasoning

Based on Critical Thinking Concepts & Tools

SECOND EDITION

RICHARD PAUL, ROBERT NIEWOEHNER and LINDA ELDER

FOUNDATION FOR CRITICAL THINKING

ROWMAN & LITTLEFIELD
Lanham • Boulder • New York • London

Contents

Introduction

Why A Thinker's Guide to Engineering Reasoning?

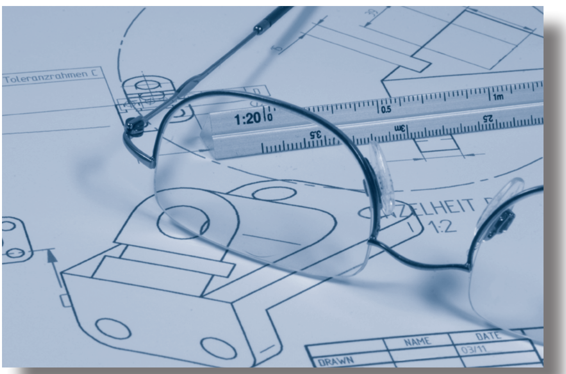
This thinker's guide is designed for administrators, faculty, and students. It contains the essence of engineering reasoning concepts and tools. For faculty it provides a shared concept and vocabulary. For students it is a thinking supplement to any textbook for any engineering course. Faculty can use 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.

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

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:

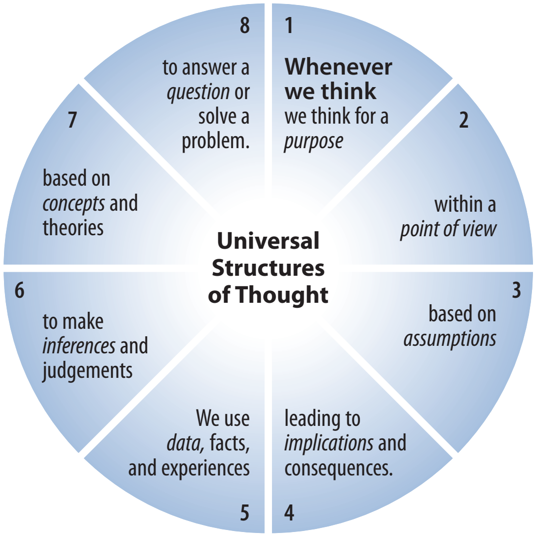
- To what extent have I analyzed the beliefs I hold which may impede my ability to think critically?
- To what extent have I demonstrated a willingness to yield my positions when sufficient evidence is presented against them?
- To what extent am I willing to stand my ground against the majority (even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

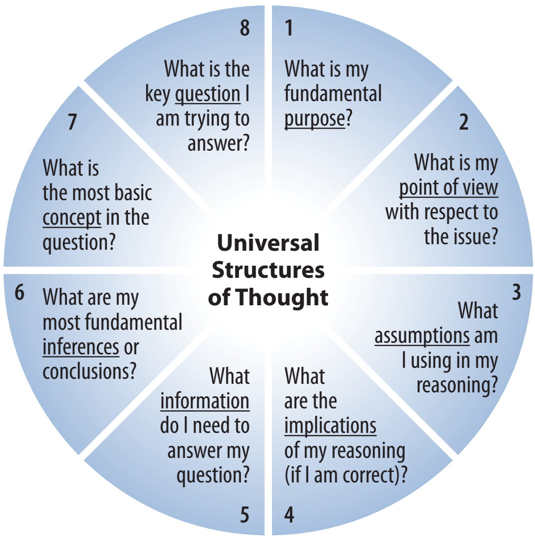
Intellectual empathy is awareness of the need to actively entertain views that differ from your own, especially those with which you strongly disagree. It entails accurately reconstructing the viewpoints and reasoning of your opponents and reasoning from premises, assumptions, and ideas other than your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

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.

Using Intellectual Standards to Assess Design Features

Clarity	Have the requirements been clearly defined (cost/schedule/performance/interoperability)? Are test standards clearly defined? What are the success criteria?
Accuracy	Are the modeling assumptions appropriate to their application? How have analytical or experimental results been confirmed?
Precision	What degree of detail is required in the design or simulation models? What is the confidence range for the supporting data? What variability can be expected in a material or manufacturing process?
Depth	Have the complexities of the problem been adequately addressed? Does the design provide appropriate interface with other current or projected systems with which it must interoperate? Has growth capability been considered/addressed? Will additional staff training or education be required? Does the design take advantage of the design space? Has software/hardware obsolescence been considered over the system lifecycle? Have end-of-life issues been identified?
Breadth	Have alternative approaches been considered? Are there alternative or emergent technologies which offer cost or performance gains?
Relevance	Does the design address the requirements? Is there unnecessary over-design? Are there unnecessary features?
Significance	Are we dealing with the most significant design issues? What factors significantly drive or constrain the design?
Fairness	Have customer/supplier interests been properly weighed? Have public or community interests been considered?

The Cost of Thinking Gone Awry

On February 1, 2003, the space shuttle Columbia disintegrated over the southern U.S., killing its crew of seven. The Columbia Accident Investigation Board (CAIB) met over the months that followed to identify the direct and indirect causes, and provide both NASA and the U.S. Congress with concrete direction with respect to the future of both the shuttle program and American manned space flight.[7] The direct technical causes of this tragedy have been widely publicized. More significantly, the CAIB reserved its most scathing findings for an institutional culture within NASA fraught with poor thinking practices that appeared to have learned nothing from the 1986 loss of the space shuttle Challenger.

Note the use of our critical thinking vocabulary in the following causal factors identified by the CAIB report, and rife throughout NASA and its contractors.

- Failure to challenge *assumptions* or patterns
- Unsupported/illogical *inferences*
- *Assumptions* confused with *inferences*
- Suppression/dismissal of *dissenting views*
- Failure to *evaluate data* quality or recognize data deficits
- Failure to weigh the full range of *implications*
- Narrow *points of view*
- Confused *purposes*
- Failure to pose the appropriate *questions*
- Application of irrelevant data and *concepts*
- Vague, equivocal language

The CAIB report specifically charged NASA leadership with a reformation of their culture to improve and encourage good thinking across the agency and its supporting contractors. The promotion of good thinking practices was to be designed into the organizational structure.

7 Gehman, HW, et. al. 2003. *Columbia Accident Investigation Board Report,* vol. 1. http://caib.nasa.gov/news/report/volume1/default.html.