"Having wandered some distance among gloomy rocks, I came to the entrance of a great cavern… Two contrary emotions arose in me: fear and desire—fear of the threatening dark cavern, desire to see whether there were any marvelous things in it."

—LEONARDO DA VINCI

SECOND EDITION

ENGINEERING REASONING

Leonardo da Vinci

Based on Critical Thinking Concepts & Tools

By DR. RICHARD PAUL, DR. ROBERT NIEWOEHNER and DR. LINDA ELDER

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FOUNDATION FOR CRITICAL THINKING

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.

Dr. AB Steyn
University of Pretoria
South Africa
May 2006

Introduction

Why A Thinker's Guide to Engineering Reasoning?

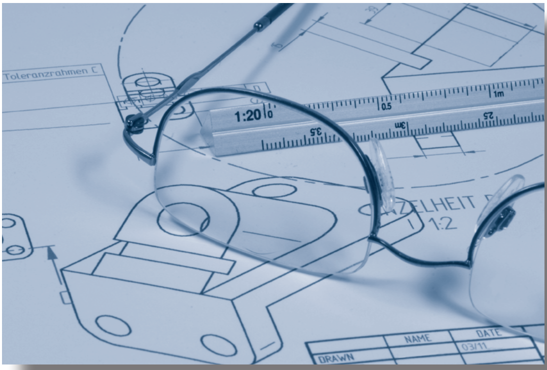
This thinker's guide is designed for administrators, faculty, and students. It contains the essence of engineering reasoning concepts and tools. For faculty it provides a shared concept and vocabulary. For students it is a thinking supplement to any textbook for any engineering course. Faculty can use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

The Standards

Clarity	Precision
Accuracy	Significance
Relevance	Completeness
Logicalness	Fairness
Breadth	Depth

Must be applied to

The Elements

Purposes	Inferences
Questions	Concepts
Points of view	Implications
Information	Assumptions

As we learn to develop

Intellectual Traits

Intellectual Humility	Intellectual Perseverance
Intellectual Autonomy	Confidence in Reason
Intellectual Integrity	Intellectual Empathy
Intellectual Courage	Fairmindedness

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 what extent do I recognize and appreciate insights in the technical views of others and recognize prejudices in my own?

Intellectual integrity consists in holding yourself to the same intellectual standards you expect others to honor (no double standards). Questions that foster intellectual integrity in engineering reasoning include:

- To what extent do I expect of myself what I expect of others?
- To what extent are there contradictions or inconsistencies in the way I deal with technical issues?
- To what extent do I strive to recognize and eliminate self-deception and bad faith in my thinking when reasoning through engineering issues?

Intellectual perseverance is the disposition to work your way through intellectual complexities despite frustrations inherent in the task. Questions that foster intellectual perseverance in engineering reasoning include:

- Am I willing to work my way through complexities in an engineering issue or do I tend to give up when challenged?
- Can I think of a difficult engineering problem in which I have demonstrated patience and tenacity?
- Do I have strategies for dealing with complex engineering issues?

Confidence in reason is based on the belief that one's own higher interests and those of humankind at large are best served by giving the freest play to reason. It means using standards of reasonability as the fundamental criteria by which to judge whether to accept or reject any proposition or position. Questions that foster confidence in reason include:

- Am I willing to change my position when the evidence leads to a more reasonable position?
- Do I aalways try to follow the evidence, without regard to my own interests?
- Do I encourage others to come to their own conclusions or do I try to coerce agreement?

Intellectual autonomy is thinking for oneself while adhering to standards of rationality. It means thinking through issues using one's own thinking rather than uncritically accepting the viewpoints, opinions, and judgments of others. Questions that foster intellectual autonomy in engineering thinking include:

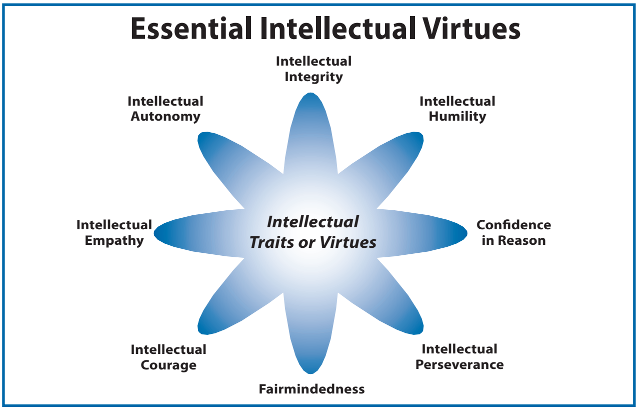
- To what extent do I uncritically accept what I am told (by my supervisors, peers, government, and so on)?
- To what extent do I uncritically accept traditional solutions to problems?
- Do I think through technical issues on my own or do I merely accept the conclusions or judgments of others?
- Having thought through an issue from a rational perspective, am I willing to stand alone against irrational criticism?

Fairmindedness is being conscious of the need to treat all viewpoints alike, without reference to one's own feelings or vested interests, or the feelings or vested interests of one's friends, company, community or nation. It implies adherence to intellectual standards without reference to one's own advantage or the advantage of one's group. Questions that foster fairmindedness include:

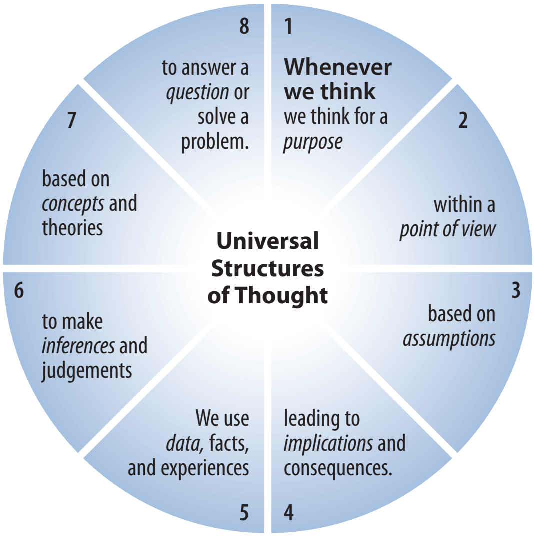
- To what extent do self-interests or biases tend to cloud my judgment?
- How do I tend to treat relevant viewpoints? Do I tend to favor some over others? And if so, why?
- To what extent do I appropriately weigh the strengths and weaknesses of all significant relevant perspectives when reasoning through an issue?
- What personal interests do we have at stake here and how can we ensure that we don't favor our own interests over the common good?

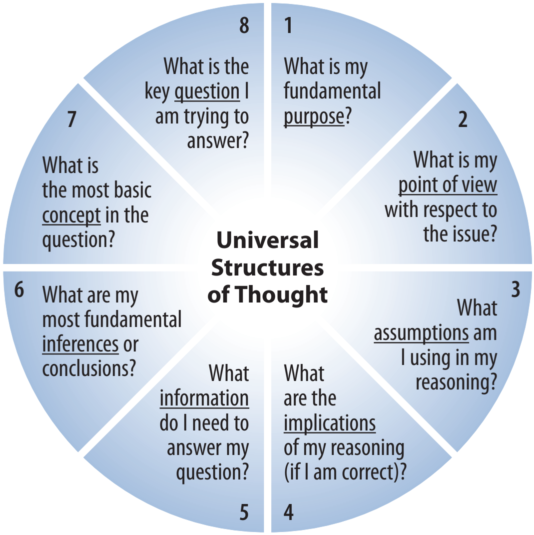
Intellectual Curiosity entails inquisitiveness as well as a strong desire to deeply understand, to figure things out, to propose and assess useful and plausible hypotheses and explanations; it implies a strong propensity to learn and to search out solutions; it propels the thinker toward further and deeper learning. Intellectually curious thinkers welcome and pursue complex, intriguing, and vexing questions. They reject superficial learning, or simplistic explanations. Intellectual perseverance is typically fueled by curiosity. The Columbia accident investigation board explicitly cited "intellectual curiosity" several times as the vital missing trait from NASA, contributing to the accident. Questions that foster intellectual curiosity in engineering reasoning include:

- To what extent do I search out new and powerful ways of addressing issues in engineering?
- To what extent do I go beyond surface explanations when dealing with complex issues?
- To what extent does my curiosity lead me to deeper insights and more powerful conceptualizations?
- To what extent do I accept traditional methods of reasoning through engineering issues, rather than seeking potentially more insightful methods?



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



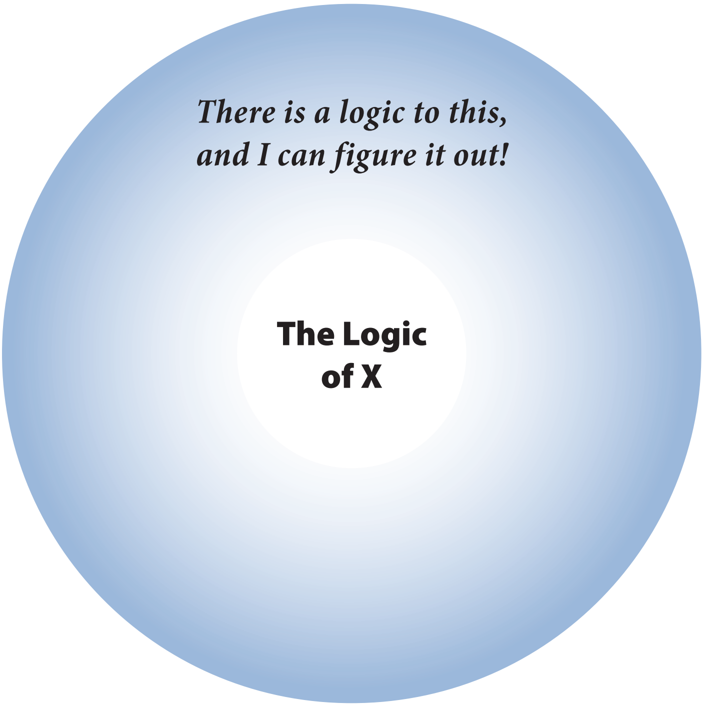


Note: When we understand the structures of thought, we ask important questions implied by these structures.

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



Be aware: Highly skilled engineers have confidence in their ability to figure out the logic of anything they choose. They continually look for order, system and interrelationships.

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, or presupposed, in the article to support his/her main arguments. Here you are looking for facts, experiences, and/or data the author is using to support her/his conclusions, as 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) ______________________.

   (Ask yourself, What is the author taking for granted [that might be questioned]? The assumptions are generalizations that the author does not think require defense 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 consequences are likely to follow if people accept the author's line of reasoning? Here you are to follow out the logical implications of the author's position. You should include implications 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 they interrelate in an engineering article, or technical report, you should be able to empathically role-play the thinking of the author. Remember, the eight basic structures of thought highlighted here define all reasoning, regardless of discipline or domain of thought. By extension, they are also the essential elements of engineering reasoning.

Analyzing a Design Using the Elements of Thought

Engineering purpose

What is the purpose of this design?
What are the market opportunities or mission requirements?
Who defines market opportunities/mission requirements?
Who is the customer?

Question at hand

What system/product/process will best satisfy the customer's performance, cost, and schedule requirements?
How does the customer define "value"?
Is a new design or new technology required?
Can an existing design be adapted?
How important is time-to-market?

Point of view

A design and manufacturing point of view is typically presumed. What other points of view deserve consideration? Stockholders? Component vendors/suppliers? Marketing/sales? Customers? Maintenance/repair/parts? Regulators? Community affairs? Politicians? Environmentalists?

Assumptions

What environmental or operating conditions are assumed?
What programmatic, financial, market or technical risks have been considered acceptable to date?
What market/economic/competitive environment is assumed?
What safety/environmental assumptions are we making? Are these assumptions acceptable?
What maturity level or maturation timeline is assumed for emerging technologies?
What happens if we change or discard an assumption?
What criteria have historically been assumed in defining a "best" or "optimum" solution?
What assumptions have been made on the availability of materials?
What manufacturing capability was assumed?
What workforce skills or attributes have been assumed?

Analyzing a Design Using the Elements of Thought (cont'd)

Engineering information

What is the source of supporting information (handbook, archival literature, experimentation, corporate knowledge, building codes, government regulation)?

What information do we lack? How can we get it? Analysis? Simulation? Component testing? Prototypes?

What experiments should be conducted?

Have we considered all relevant sources?

What legacy solutions, shortcomings, or problems should be studied and evaluated?

Is the available information sufficient? Do we need more data? What is the best way to collect it?

Have analytical or experimental results been confirmed?

What insights and experiences can the shop floor provide?

Concepts

What concepts or theories are applicable to this problem?

Are there competing models?

What emerging theory might provide insight?

What available technologies or theories are appropriate?

What emerging technologies might soon be applicable?

Inferences

What is the set of viable candidate solutions?

Why were other candidate solutions rejected?

Is there another way to interpret the information?

Is the conclusion practicable and affordable?

Implications

What are some important implications of the data we have gathered?

What are the most important market implications of the technology?

What are the most important implications of a key technology not maturing on time?

How important is after-market sustainability?

Is there a path for future design evolution and upgrade?

Are there disposal/end-of-service-life issues we need to consider?

What are the most important implications of product failure?

What design features if changed, profoundly affect other design features?

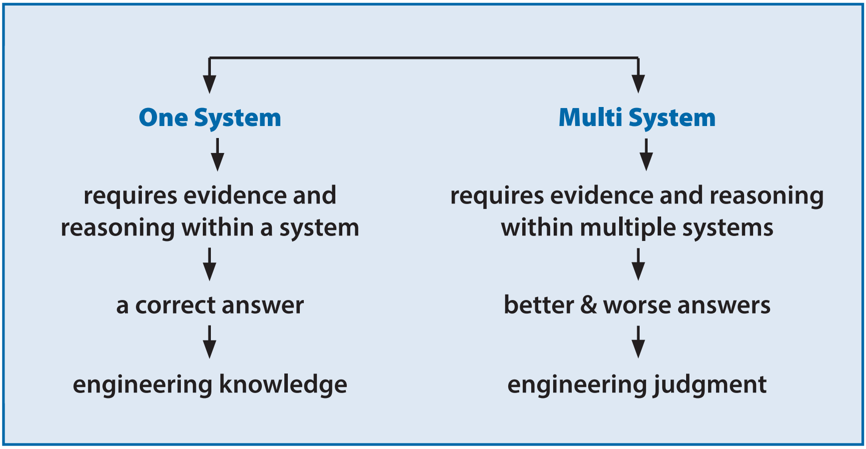
What design features are insensitive to other changes?

What potential benefits do by-products offer?

Should social reaction and change management issues be addressed?

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.

Analyzing Disciplines: Electrical Engineering

Purpose. Electrical engineering develops electrical and electronic systems for public, commercial, and consumer markets. It is tremendously broad, spanning many domains including recreational electronics, residential lighting, space communications, and electrical utilities.

Key Questions. What are the detailed design features of the system that best satisfy the stated mission or market requirements? How will we conceive, design, implement, and operate electrical and electronic products and systems?

Point of View. The point of view is commonly that of the design and manufacturing team. Other relevant points of view include the customer, stockholders, marketing, maintainers, or operators.

Key Concepts. These concepts include electromagnetism (Maxwell's equations), electrochemical properties of materials, discrete and analog mathematics, resistance, current, charge, voltage, fields and waves, and so on.

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, and that those principles can be used to model electrical systems. Electrical engineers assume that some important market needs can be best met through electrical and electronic products. Additionally, electrical engineers frequently assume that their work must be integrated with other engineering disciplines (such as mechanical, chemical, and so forth) in the design and implementation of a product.

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

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

Implications. Electrical engineering products and services have wide-ranging implications that span global, national, and local economics, public infrastructure, health care, and communications, with potential for positive and negative quality of life impacts on communities and regions.

Analyzing Disciplines: Mechanical Engineering

Purpose. Mechanical engineering develops mechanical systems and materials for public, commercial, and consumer markets. It is tremendously broad, spanning transportation, mechanisms, architecture, energy systems, materials, and more.

Key Questions. What are the detailed design features of the mechanical system that best satisfy the stated mission or market requirement? How will we conceive, design, implement, and operate mechanical components, products, and systems?

Point of View. Commonly, the point of view is that of the design and manufacturing team. Other relevant points of view include the customer, stockholders, marketing, maintainers, or operators.

Key Concepts. These concepts include materials science, stress, strain, loads, friction, dynamics, statics, thermodynamics, fluid mechanics, energy, work, CAD/CAM, machines, and so on.

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, and that those principles can be used to model mechanical systems. Mechanical engineers assume that market needs can be met with mechanisms and materials. Additionally, mechanical engineers frequently must integrate their work with other engineering disciplines (such as automotive, aerospace, electrical, computer, chemical, and so forth) in the design and implementation of a product.

Data or Information. Mechanical engineers require experimental and computational data, legacy designs, regulatory requirements, market studies or mission need statements.

Inferences, Generalizations, or Hypotheses. The conclusion of most mechanical engineering activity is a product ready for delivery to a customer, or integration into a larger system.

Implications. Mechanical engineering products and services have wide-ranging implications that span global, national, and local economics, public infrastructure, transportation, health care and communications with potential for positive and negative quality of life impacts on communities and regions.

Braine-le-Château (Belgium), the old community watermill on the Hain river. Picture by Jean-Pol GRANDMONT

Analyzing Engineering Tools: Modeling and Simulation

Purpose. Modeling and simulation can either be a direct engineering product or a development tool used to design other complex systems. It provides a representation of the physical world for purposes such as operator training, development trade studies, component development, prototype testing, and test and evaluation where full-scale live testing is impractical, dangerous or cost-prohibitive.

Key Questions. How can the features of the real world be practically simulated to provide accurate insight into physical interactions and behaviors in order to design physical systems for specific purposes? What level of detail is required for accurate portrayal of the systems behavior?

Point of View. Simulation and modeling takes the point of view that the physical world submits to mathematical and computational modeling to such an extent that the behaviors observed in simulation reliably imitate or predict a system's performance in the real world.

Key Concepts. Concepts span all domains of engineering, but also notably include concepts such as numerical methods, equations of motion, man-the-loop and hardware-in-the-loop testing, batch simulation, virtual reality, display latency, systems identification and computational throughput.

Key Assumptions. Simulation depends upon simplifying assumptions; real world detail remains beyond our reach. Simple simulations entail lengthy lists of assumptions. Improving simulation fidelity entails adding details to physical models that are assumed negligible in more simple models. Enhancing fidelity to the real physical world means removing assumptions, and consequently building complexity.

- When using modeling and simulation, engineers assume that they can design models that accurately represent the physical world to a sufficient level of detail.
- Simulation and modeling typically assumes that a relationship exists between cost and complexity, value and fidelity.
- Engineers assume that there are situations in which modeling and simulation provides vital insight (note that simulation may be employed throughout the product life, from conception to operation), while simultaneously recognizing that unmodeled phenomena may indeed be significant (limiting the simulations value).

The Data or Information. The information upon which simulation and modeling depends includes math models for the interaction of simulated systems, plus specific attributes of physical systems provided by analysis, physical testing, legacy designs, or systems identification.

Inferences. Simulation conclusions include design decisions as well as training and educational practices.

Implications. Simulation can reduce the risk or expense of engineering development and testing, or provide insight into a system's response to conditions which cannot practically or safely be tested in realistic conditions (e.g., failure states or emergency conditions). However, if a simulation product or process is flawed, negative implications might exist for the use of the actual product when used in the real world.

Skilled Engineers Consentingly Adhere to Intellectual Standards

Universal intellectual standards must be applied to thinking whenever one is evaluating the quality of reasoning as one reasons through problems, issues, and questions. These standards are not unique to engineering, but are universal to all domains of thinking. To think as a highly skilled engineer entails having command of these standards and regularly applying them to thought. While there are a number of universal standards, we focus here on some of the most significant.

Clarity: Understandable; the meaning can be grasped

Clarity is a gateway standard. If a statement is unclear, we cannot determine whether it is accurate or relevant. In fact, we cannot tell anything about it because we do not yet know what it is saying.

Questions targeting clarity include the following.

- Could you elaborate further on that point?
- Could you express that point in another way?
- Could you give me an illustration or example?
- Are the market/mission requirements clearly stated?
- Have terms and symbols been clearly defined?
- Which requirements have priority and which can be relaxed if required?
- Have the assumptions been clearly stated?
- Is specialized terminology either defined, or being used in keeping with educated usage?
- Do drawings/graphs/photos and supporting annotations clearly portray important relationships?[3]
- How do the affected stakeholders define "value"?

Accuracy: Free from errors or distortions; true

A statement can be clear but not accurate, as in "Most creatures with a spine are over 300 pounds in weight."

Questions targeting accuracy include the following.

- Is that really true?
- How could we check that?
- How could we find out if that is true?
- What is your confidence in that data?
- Has the test equipment been calibrated? How or when?

[3] See pp. 27-28 for further questions that target the assessment of graphics through intellectual standards. Students and faculty interested in clarity of graphical communication are urged to read these three books by Edward Tufte: *Visual Explanations, Envisioning Information*, and *The Visual Display of Quantitative Information*. Published by Graphics Press, Cheshire, Connecticut.

- How have simulation models been validated?
- Have assumptions been challenged for legitimacy?
- What if the environment is other than we had expected (e.g., hotter, colder, dusty, humid)?
- Are there hidden or unstated assumptions that should be challenged?

Precision: Exact to the necessary level of detail

A statement can be both clear and accurate, but not precise, as in "The solution in the beaker is hot." (We don't know how hot it is.)

Engineering questions targeting precision include the following.

- Could you give me more details?
- Could you be more specific?
- What are acceptable tolerances for diverse pieces of information?
- What are the error bars or confidence bounds on experimental, handbook or analytical data?
- At what threshold do details or additional features no longer add value?

Concision: Brief in form while comprehensive in scope, implies the elimination of unnecessary details to clarify thought

Concision does not connote eliminating words for brevity's sake (the sound bite), but rather an economy of thoughts whereby the thinking is deep and significant, and clarity is actually enhanced by the limited use of words. The question – or questions – at issue, and the context within which the question is situated, determine the amount of detail needed to clarify or guide thought in a given situation. In other words the question, and its context, drive the level of detail (precision/concision) needed. In the hours building to the loss of the Space Shuttle Challenger, engineers understood the peril faced by launching at extremely low temperatures. Yet, they buried their management in insignificant details such that their message was missed; their signal was lost in self-generated noise. "Clear and concise" appear routinely in business writing guides as almost inseparable expectations of business leaders. In his Principia, Isaac Newton remarked, "More is vain when less will serve."

Questions targeting concision include the following:

- What can I remove that will boost the clarity of my point?
- Do I need to eliminate any distracting details?
- Should I move some of the relevant data to an appendix where it is available but less distracting (because less important)?
- Can a graph more concisely present this tabulated data, and boost the clarity of the data being presented and the variables being considered?

Relevance: Relating to the matter at hand

A statement can be clear, accurate, and precise, but not relevant to the question at issue. A technical report might mention the time of day and phase of the moon *at which the test was conducted. This would be relevant if the system under test were a night vision device. It would be irrelevant if it were a microwave oven.*

Questions targeting relevance include the following.

- How is that connected to the question?
- How does that bear on the issue?
- Have all relevant factors been weighed (e.g., environmental, or marketplace)?
- Are there unnecessary details obscuring the dominant factors?
- Has irrelevant data been included?
- Have important interrelationships been identified and studied?
- Have features and capabilities (and hence costs) been included which the customer neither needs nor wants?

Depth: Containing complexities and multiple interrelationships

A statement can be clear, accurate, precise, and relevant, but superficial. For example, the statement, "Radioactive waste from nuclear reactors threatens the environment," is clear, accurate, and relevant. Nevertheless, more details and further reasoning need to be added to transform the initial statement into the beginnings of a deep analysis.

Questions targeting depth include the following.

- How does your analysis address the complexities in the question?
- How are you taking into account the problems in the question?
- Is that dealing with the most significant factors?
- Does this design model have adequate complexity and detail, given its counterpart in reality?

Breadth: Encompassing multiple viewpoints

A line of reasoning may be clear, accurate, precise, relevant, and deep, but lack breadth (as in an argument from either of two conflicting theories, both consistent with available evidence).

Questions targeting multiple viewpoints include the following.

- Do we need to consider another point of view?
- Is there another way to look at this question?
- What would this look like from the point of view of a conflicting theory, hypothesis, or conceptual scheme?
- Have the full range of options been explored?
- Have interactions with other systems been fully considered?

Logic: The parts make sense together, no contradictions

When we think, we bring a variety of thoughts together into some order. The thinking is "logical" when the conclusion follows from the supporting data or

Questions/Statements targeting logic include the following.

- Does this really make sense?
- Does that follow from what you said? How does that follow?
- But earlier you implied this and now you are saying that. I don't see how both can be true.
- Are the design decisions supported by logical analysis?

Fairness: Justifiable, not self-serving or one-sided

Fairness is particularly at play where more than one viewpoint is relevant to understanding and reasoning through an issue (conflicting conceptual systems), or where there are conflicting interests among stakeholders. Fairness gives all relevant perspectives a voice, while recognizing that not all perspectives may be equally valuable or important.

Questions targeting fairness include the following.

- Have other points of view been considered (stock holders, manufacturing, sales, customers, maintenance, public citizens, community interests, and so on)?
- Are vested interests inappropriately influencing the design?
- Are divergent views within the design team given fair consideration?
- Have the environmental/safety impacts been appropriately weighed?
- Have we fully considered the public interest?
- Have we thought through the ethical implications in this decision?

Significance: Important, of consequence

Our thought can be clear, accurate, precise, and relevant, yet be trivial, or fail to focus on significant issues or problems. Engineering frequently entails problems with multiple relevant independent variables, and yet one or two out of a half dozen may outstrip the others in importance or significance. Students can grasp at anything that comes to mind that's relevant, and yet miss the significant. This is also common in poorly run meetings, in which minor matters consume inordinate time, and vital issues get short shrift or are ignored entirely. Attentiveness to the significant results in recognizing the most important information, issues and implications in engineering reasoning.

Questions targeting significance include the following:

- Have we identified the most important questions at the heart of the issue?
- What are the most influential factors?
- What are the important variables that need to be considered?
- What are the most significant implications that must be reasoned through as we design this project?

Universal Intellectual Standards Essential to Sound Engineering Reasoning

Clarity	Could you elaborate further? Could you give me an example? Could you illustrate what you mean?
Accuracy	How could we check on that? How could we find out if that is true? How could we verify or test that?
Precision	Could you be more specific? Could you give me more details? Could you be more exact?
Relevance	How does that relate to the problem? How does that bear on the question? How does that help us with the issue?
Depth	What factors make this a difficult problem? What are some of the complexities of this question? What are some of the difficulties we need to deal with?
Breadth	Do we need to look at this from another perspective? Do we need to consider another point of view? Do we need to look at this in other ways?
Logic	Does all this make sense together? Are we taking a reasonable approach to the problem? Does what you say follow from the evidence?
Significance	Is this the most important problem to consider? Is this the central idea to focus on? Which of these facts are most important?
Fairness	Am I considering the views of others in good faith? Am I accurately representing the viewpoints of others? Is there an ethical component to this issue that we are avoiding for reasons of vested interest?

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?

Using Intellectual Standards to Assess Graphics

Technical documents and presentations commonly rely upon photographs, illustrations, and graphs to communicate content. Graphics are prominent because: (1) graphics can be very information dense; (2) graphics can reveal comparisons and trends that would be obscure in tabular data or text; and (3) graphics can reveal interconnections and relationships that are difficult to capture within the linear flow of text. Graphics *can* do these things, but *don't necessarily* do these things. Graphical evidence can also trivialize, mislead, obscure, or confuse.

Professor Edward Tufte (Yale) emphasizes the following paragraph as the most important message in any of his books on graphical communications.

> Visual representations of evidence should be governed by principles of reasoning about quantitative evidence. For information displays, design reasoning must correspond to scientific reasoning. Clear and precise seeing becomes as one with clear and precise thinking.[4]

Thus, intellectual standards apply to graphical communication as well as they do to other forms of information!

Clarity

- Will color enhance this graphic's clarity? (Frequently, "Yes")
- Must I plan for black and white reproduction? (Also frequently, "Yes")
- Have symbols been defined? Could annotation replace symbols?
- Are units of measure clearly labeled?
- Are consistent units and axes warranted?
- Must the graphic stand by itself? Alternatively, can it rely on nearby text?
- Could multiple graphs be overlaid to improve comparisons?
- Is data running together? Should these graphs be separate?

Precision

- Will this graphic be presented on paper, or must I account for low-resolution media, which lose detail (e.g., web or computer projection)?
- Have I chosen appropriate axes? Should one axis be logarithmic?
- Would confidence bands or error bars improve credibility?

Accuracy

- Is the choice of perspective or axes misleading?
- Are observed trends realistically portrayed or illegitimately amplified or attenuated by visual gimmick or distorted axes?

[4] Tufte E. 1997. *Visual Explanations*. Cheshire, Connecticut: Graphics Press, 53.

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