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A Critical Thinking Model for Engineering

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ABSTRACT

Richard Paul's model for critical thinking is adapted to the challenge of engineering education. The model is briefly described and exemplified by questions asked by engineers in practice. The paper concludes with exercises suitable for the undergraduate and graduate engineering program.

INTRODUCTION

The analysis and evaluation of our thinking as engineers requires a vocabulary of thinking and reasoning. The intellect requires a voice. Richard Paul and Linda Elder, from the Foundation for Critical Thinking, have proposed a critical thinking model documented in various sources ([1], [2] and [3]), including over a dozen *Thinkers' Guides* that apply this model to diverse disciplines (e.g.- [4]).

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. Here we apply a model to the way in which we think, an architecture whose purpose is aiding the analysis and evaluation of thought, that we might improve our thought. A new thinkers' guide, *Engineering Reasoning* [5], applies this model to the engineering enterprise. This paper introduces this *Thinkers' Guide* as a tool for engineering educators and students, summarizing its content and suggesting several exercises for its use in support of engineering course and project work.

The guide follows Paul's model, providing a framework for analyzing and evaluating engineering reports, designs, graphics, and entire disciplines. It articulates the questions that exemplify maturing engineering reasoning. Several examples are provided of both excellence and disaster in engineering reasoning. The model is also applied to areas which touch engineering such as creativity, craftsmanship, and ethics.

THE PROBLEM

Elder [6] cites a series of studies of higher education indicating that college faculty almost unanimously insist that the promotion of critical thinking ranks among the primary goals of their work. Lamentably, that same body of research indicates that few college professors can articulate a substantive understanding of critical thinking, and few can identify the elements of their teaching that specifically develop critical thinking. Reference [6] appeals for the development of a substantive view of critical thinking both within and across college faculties.

THE CDIO SYLLABUS AND CRITICAL THINKING

The CDIO consortium has developed a comprehensive syllabus for an engineering education, ratified by diverse international industry and academic leaders. The syllabus articulates a diverse range of learning objectives, many of which explicitly employ the language of critical thinking or implicitly touch upon the thinking capabilities of our students. Each of the below skills are cited by the syllabus as objectives in the lives of the undergraduate engineering student (numbers in parentheses refer each item's location with the CDIO syllabus)

Engineering Affective Dimensions

- exercising independent thought and judgment (2.4.2)
- exercising reciprocity (2.4.2)
- welcoming ingenuity and innovation (2.4.1, 2.4.3)
- recognizing diverse stakeholder points of view (2.3.1, 4.1.6)
- suspending judgment (2.4.2)
- developing insight into egocentrism and sociocentrism (2.4.2)

Cognitive Dimensions: Engineering Macro-Abilities

- selecting critical questions to be answered (2.2.1)
- clarifying technical issues and claims (2.2.1)
- clarifying technological ideas (2.1, 2.2, 3.2)
- developing criteria for technical evaluation (4.4.6)
- evaluating scientific/engineering authorities (2.2.2)
- raising and pursuing root questions(2.2.1)
- evaluating technical arguments (2.4.4)
- generating and assessing solutions to engineering problems (2.1)
- identifying and clarifying relevant points of view (4.2)
- engaging in Socratic discussion and dialectical thinking on engineering issues
- avoiding oversimplification of issues
- developing engineering perspective (4.x)

Cognitive Dimensions: Engineering Micro-Skills

- evaluating data (2.1.1)
- analyzing assumptions (2.1.1)
- identifying and applying appropriate models (2.1.2)
- explaining generalizations (2.1.3)
- questioning incomplete or ambiguous information (2.1.4)
- analyzing essential results of solutions and test data (2.1.5)
- reconciling discrepancies in results (2.1.5)
- making plausible engineering inferences (2.1)
- supplying appropriate evidence for a design conclusion (4.4)
- recognizing contradictions
- recognizing technical, legal/regulatory, economic, environmental, and safety implications and consequences (4.1.1)
- distinguishing facts from engineering principles, values, and ideas

A CRITICAL THINKING MODEL

To address Elder's observation above, the analysis and evaluation of our thinking as engineers requires a vocabulary of thinking and reasoning. The intellect requires a voice. The model that follows is not unique to engineering; indeed, its real power is its flexibility in adapting to *any* domain of life and thought. Other *Thinkers' Guides* apply this model 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. Here we apply a model of the way in which we think, an architecture whose purpose aides the analysis and evaluation of thought, that we might improve our thought.

The model depicted in Figure 1 provides an overview of Paul's model, which the guide develops, working from the base of the diagram up. The goal is the mature engineering thinker, and so that endpoint is described first with a brief discussion of the intellectual virtues as might be expressed in the practice of engineering.

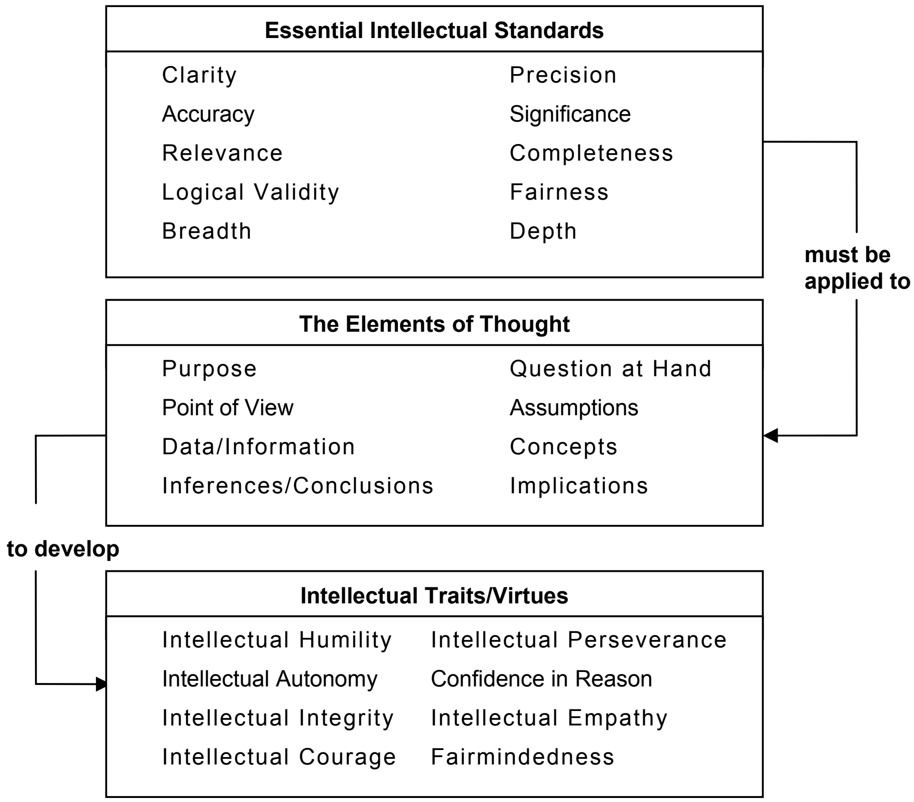

Figure 1: Richard Paul's Critical Thinking Model.[1]

Subsequently, the eight elements of thought are introduced. These are the tools for the *analysis* of thinking in oneself and others. 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. The guide weaves the standards together with the elements in several formats to demonstrate application of these *evaluation* standards to our *analysis* products.

Finally, this paper outlines exercises which can be used in the context of engineering studies.

INTELLECTUAL TRAITS ESSENTIAL TO ENGINEERING REASONING

The engineer does not work in isolation, but in the context of enterprises, cultures and communities, each of which represents divergent interests and perspectives. Furthermore,

[1] Adapted from ref [4], pg 24.

no engineer can claim perfect objectivity; their work is unavoidably influenced by strengths and weaknesses, education, experiences, attitudes, beliefs, and self-interest. They avoid paths they associate with past mistakes and trudge down well worn paths that worked in the past. The profession engineer must cultivate personal and intellectual virtues.

These virtues are not radically distinct from those sought by any maturing thinker. They determine the extent to which we think with insight and integrity, regardless of the subject. The engineering enterprise does however pose distinct questions for the engineer in pursuit of such virtue.

Intellectual humility admits to ignorance, frankly sensitive 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 work this issue?
- Am I quick to admit when I'm in domains beyond my expertise?
- Am I open to consider 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 enterprise culture and any sub-culture 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 our own, especially those with which we strongly disagree. It entails accurately reconstructing the viewpoints and reasoning of our opponents and to reason from premises, assumptions, and ideas other than our own. Questions that foster intellectual empathy include:

- Do I listen and seek to understand others' reasoning?
- Do I accurately represent viewpoints with which I disagree?
- Do I accurately represent opponents' views? would they agree?
- Do I recognize and appreciate insights in the technical views of others and 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?

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[2] *Code of Ethics for Engineers*, National Society of Professional Engineers, January, 2003 [www.nspe.org/ethics/codeofethics003.pdf]

- To what extent do I strive to recognize and eliminate self-deception or self-interest when reasoning through engineering issues?

Intellectual perseverance is the disposition to work your way through intellectual complexities despite the frustration 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?

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 when thinking as engineers include:

- Am I willing to change my position when the evidence leads to a more reasonable position?
- Do I adhere to technical principles and evidence when persuading others of my position or do I distort matters to support my position?
- Do I encourage others to come to their own technical 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 reasoning include:

- Do I think through technical issues on my own or do I merely accept others' conclusions or judgments?
- 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; implies adherence to intellectual standards without reference to one's own advantage or the advantage of one's group.

- Am I giving dissenting opinions adequate consideration?
- Has self-interest or bias clouded my judgment?
- Have I adequately thought through the potential hazards to others?

ALL THINKING INVOLVES FUNDAMENTAL ELEMENTS

All thinking entails eight fundamental elements, whether it is about engineering, philosophy, cooking, sports, or business. These elements provide a framework for questions we can pose to evaluate our thinking or the thinking of others.

> "WHENEVER WE THINK, we think for a *purpose* within a *point of view*, based on *assumptions*, leading to *implications* or consequences. We use *data*, facts and experiences, to make *inferences* and judgments, based on *concepts* and theories, to answer a *question* or solve a problem."[3]

These eight elements, whether recognized or not, are present whenever we think about *any* subject. Table 1 below illustrates common questions in engineering practice organized around these eight elements.

[3] Ref [1]. pg. 68

Table 1. Analyzing a Design Using the Elements of Thinking

Engineering Purpose	- What's the purpose of this design? - What is the market opportunity 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? Stock-holders? 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 are being accepted? - What market/economic/competitive environment is assumed? - What safety/environmental risks are unacceptable? - What maturity level or maturation timeline is assumed for emerging technologies? - What happens if we relax or discard an assumption? - What criterion will define 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?
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? How may it be collected? - 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?

Table 1 (continued). Analyzing a Design Using the Elements of Thinking

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 the implications of the supporting data? - What are the market implications of the technology? - What are the 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? - What are the implications of product failure? - What design features if changed, profoundly impact 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?'

ENGINEERING REASONING APPLIES INTELLECTUAL STANDARDS

Universal intellectual standards must be applied to thinking whenever one is interested in checking the quality of reasoning about a problem, issue, or situation. The standards are not unique to engineering, but are universal to all domains of thinking. To think professionally as an engineer entails having command of these standards. While there are a number of universal standards, we focus here on some of the most significant:

Clarity

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 don't yet know what it is saying."Could you elaborate further on that point?" "Could you express that point in another way?" "Could you give me an illustration or example?" Specific clarity questions in engineering include:

- 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 being used consistent with conventions?
- Do drawings/graphs/photos and supporting annotations clearly portray important relationships?
- How do the affected stakeholders define "value"?

Accuracy

A statement can be clear but not accurate, as in "Most creatures with a spine are over 300 pounds in weight." "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?"
Specific clarity questions include:

- Has the test equipment been calibrated? How/when?
- How have simulation models been validated?
- Have assumptions been challenged for legitimacy?

Precision

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. "Could you give me more details?" "Could you be more specific?") Specific precision questions include:

- What are acceptable tolerances for diverse pieces of information?
- What are the error bars or confidence bounds on experimental, handbook or analytical data?

Relevance

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 was a night vision device. It would be irrelevant if it had been a microwave oven. "How is that connected to the question?" "How does that bear on the issue?"

Engineers might ask questions of relevance:

- 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 cost) been included which the customer neither needs nor wants?

Depth

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, it lacks depth because it treats an extremely complex issue superficially. (It also lacks precision.) "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?" Specific depth questions include:

- Do design models have adequate complexity and detail?
- At what threshold does detail or additional features stop adding value?

Breadth

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). "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?" For the engineer, specific breadth questions include:

- Have the full range of options been explored?
- Have interactions with other systems been fully considered?
- What if the environment is other than we had expected (e.g.- hotter, colder, dusty, humid)?

Logical Validity

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 propositions. The conclusion is “illogical” when it contradicts proffered evidence, or the arguments fail to cohere." Does this really make sense?" "Does that follow from what you said? How does that follow?" "But before you implied this and now you are saying that, I don’t see how both can be true." For the engineer, specific logic questions include:

- Are the design decisions supported by good analysis?

- Are there hidden or unstated assumptions which should be challenged?

Fairness

Fairness is particularly at play where either a problem has multiple approaches (conflicting conceptual systems), or conflicting interests among stake-holders. Fairness gives all perspectives a voice, while recognizing that all perspectives may not be accurate or equally valuable.

- Have other points of view been considered (stock holders, manufacturing, sales, customers, maintenance, public citizens, community interests, etc.)?
- 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 I considered the public interest?

Table 2 illustrates the standards in the form of questions that might commonly arise in evaluating an engineering design.

Table 2. Design Evaluation Questions Provoked By the Intellectual Standards

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 fidelity is required in the design or simulation models?
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?
Breadth	Have alternative approaches been considered? Are there alternative or emergent technologies which offer cost or performance gains? Does the design take advantage of the design space? Has software/IT hardware obsolescence been considered over the system lifecycle? Have end-of-life issues been identified?
Relevance	Does the design address the requirements? Is there unnecessary over-design? Are there unnecessary features?
Significance	What are the significant design drivers?
Fairness	Have customer/supplier interests been properly weighed? Have public or community interests been considered?
Logical Validity	Do design decisions flow from appropriate analysis?

USING THE MODEL IN ENGINEERING EDUCATION

The following critical thinking exercises can employ the *Engineering Reasoning Mini-Guide* [5] as an in class supplement (suggested).

Intellectual Traits

Engineering students are likely puzzled at first by the suggestion that personal virtues relate to their success as engineers. The criticality of these traits becomes prominent in their interactions as members of teams. Consequently, introducing the standards and using them to foster development, is most effectively done in the context of their efforts to make their teams succeed.

As an introduction to the standards, and prior to commencing team efforts, students should read the descriptions and then discuss ensemble the value of these diverse traits. The questions they specifically want to discuss are why any of these traits will be beneficial to their team's success, and why the absence of these traits will likely hinder the team's performance.

At the conclusion of team projects, or coincident with major milestones (long duration projects), team members can be assigned to write a paragraph in which they identify a vignette in which they saw one of the intellectual traits exhibited in a way that benefited the team, and a second example identifying a vignette in which an individual or team deficit in the intellectual traits hampered team performance. The faculty member or team manager should then collate the vignettes stripping contributors' names (recognizing the team manager may be the subject of either positive or negative vignettes). A group discussion of the results should be included as part of technical debrief.

Elements of Reasoning

The real power in this taxonomy of thinking is its scalability. A topic as large as an entire course or as small as an editorial in the newspaper or a single lecture can be decomposed using the elements. The student can be asked to decompose a journal article, course topic, textbook chapter or technical report using this framework. Opportunities abound for using the eight elements both in class and outside course-work.

The eight elements can be introduced to the students in several ways. The guide includes a number of templates and examples. The most effective way for the students to become comfortable working with the elements is to review an example and then immediately apply the template to some subject area.

On the opening day of a class, the entire class can be asked to identify the eight elements associated with the prerequisite course, e.g.- "Identify the eight elements associated with the class you finished last semester in Aerodynamics. What was the purpose of Aerodynamics? What question was it trying to answer? What was the point of view? What assumptions were commonly made? What information was brought to bear? What concepts were key? What conclusions were formed? What were the implications of the material you learned?" Once students were given 6-8 minutes to do this individually, they could then share their answers either in small groups, or as a class. They could then be assigned to skim their new text's Table of Contents and decompose the new course according to the same template.

The faculty member is indispensable in keeping the elements close to the surface of the students thinking. This is best done by Socratic interaction in which the questions posed by professor apply to one of the eight elements: "What were the assumptions constraining this approach?" "What implications follow from this development?" "When we started to derive this relationship, what question are we trying to answer?" "What's the source of this insight? Was it theoretical or experimental? What empirical support do we have for this theoretical result?"

At the end of a course segment or at the end of the course, the students can be tasked to decompose that chapter's content or the entire course using the 8 elements. At any point during the course, the content of a relevant article can be decomposed.

The value of this practice is helping the student to provide a context for that segment or course. It provides a framework for recalling the importance of assumptions, recalling the big picture question at hand, and wrestling with implications.

Intellectual Standards

The most effective means of introducing the intellectual standards is by means of reciprocal teaching. Using the *Engineering Reasoning* guide, students should be assigned in pairs to read the descriptions and example questions associated with *Clarity* and *Accuracy* (one student assigned to each). They should be given 3-4 minutes to prepare to explain their assigned standard to their partner, including both examples of representative questions from the guide, as well as an example they've created themselves.

In class, the standards provide a template for developing good questions to be posed in Socratic fashion. In doing so, the professor is modelling the thinking of mature engineers through the questions they pose. The questions from the Table 2 above

Many of us struggled as new faculty trying to identify the most valuable feedback we could provide our students. On technical reports, for example, what comments can I provide a student that will best promote their learning from this experience. The standards provide a ready vocabulary for identifying the weaknesses in student work. Moreover, if the professor's feedback consistently appeals to the standards either explicitly or implicitly, and holds students to those standards, students will be more inclined to embrace the standards as the goal they are striving to achieve.

Ancillary material

Vignettes in the back of the guide are intended to illustrate both successes and failures in engineering in our critical thinking vocabulary. They are included to foster discussion portraying the results of both excellent and deficit engineering reasoning. Students can be encouraged to research other historical examples and specifically evaluate how the success or failure of a technical enterprise turned on the quality of thought. While we commonly dissect accidents for their technical and organizational flaws, it is also illuminating to evaluate the thinking present in these episodes.

CONCLUSIONS

Our students' critical thinking implicitly undergirds all the desired skills found in the CDIO syllabus. As with other engineering endeavours, models are invaluable in understanding and articulating the connections and interactions of systems and environments. This paper applied a model of critical thinking to the mind of the mature engineer, with the goal of helping us understand how to describe our own thinking and hence better develop the thinking of engineering students. It also provided a brief list of ideas for directly applying the content to the engineering classroom.

ACKNOWLEDGEMENTS

I must necessarily thank Richard Paul and Linda Elder for their decades of work as champions of critical thinking in education. It's been a delight to learn from them and collaborate in the preparation of the *Engineering Reasoning* guide from which this paper has been adapted.

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