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Applying a critical thinking model for engineering education

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ABSTRACT: Richard Paul's critical thinking model was adapted to the challenge of engineering education and published in July 2006 as a guide to *Engineering Reasoning*. Paul's model is briefly described and exemplified by questions that engineers ask in practice. In this article, the author describes classroom exercises that employ the model, which have been developed and suggested by partners of the *Conceive – Design – Implement – Operate* (CDIO) Initiative for use in undergraduate and graduate engineering programmes.

INTRODUCTION

The evaluation of our thinking as engineers requires a vocabulary of thinking and reasoning. Critical thinking is found in diverse accreditation standards and the CDIO Syllabus. Paul and Elder, from the Foundation for Critical Thinking, have proposed a critical thinking model documented in various sources (eg refs [1-3]), including over a dozen *Thinkers' Guides* that apply this model to diverse disciplines (eg ref. [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, a model is applied to the way in which we think, an architecture whose purpose is aiding the analysis and evaluation of thought to improve thinking. A new thinkers' guide, *Engineering Reasoning*, was developed by the Foundation for Critical Thinking and members of the CDIO Initiative, applying this model to the engineering enterprise [5]. In this article, the author introduces this *Thinkers' Guide* as a tool for engineering educators and students, summarising 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 analysing 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 that touch engineering, such as creativity, craftsmanship and ethics.

THE PROBLEM

Elder cites a series of studies indicating that college faculty almost unanimously insist that promoting critical thinking ranks among the primary goals of their work [6]. Lamentably, that same 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. Elder urges a substantive view of critical thinking within higher education.

A CRITICAL THINKING MODEL

Engineers and scientists are quite comfortable working within the context of conceptual models. Paul's model of the way in which engineers think is employed here, providing an architecture whose purpose aids the analysis and evaluation of thought so as to improve our thoughts (see Figure 1). The model is not unique to engineering; indeed, its real power is its flexibility in adapting to *any* domain of thought, as treated in other *Thinkers' Guides*.

ESSENTIAL INTELLECTUAL TRAITS

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

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

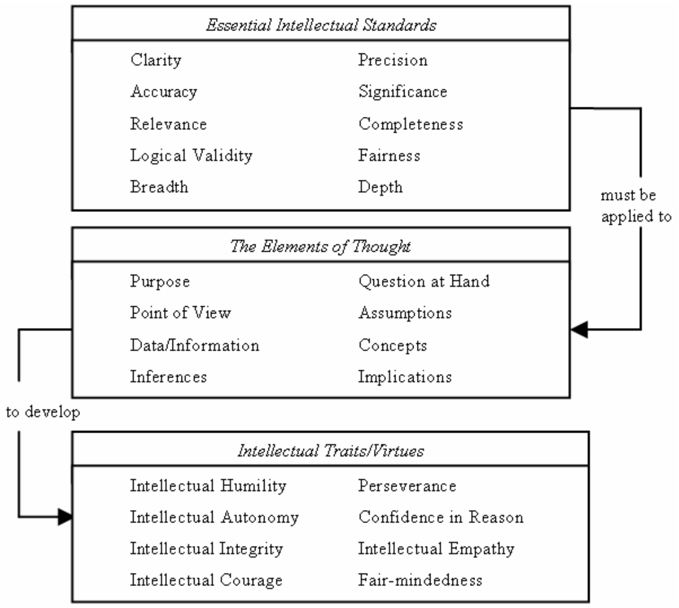

Figure 1: Richard Paul's Critical Thinking Model (adapted from ref. [4]).

The *humble* engineer asks:

- Does my experience really qualify me to work this issue? Am I quick to admit when I am in domains beyond my expertise?
- To what extent do my prejudices, attitudes or experiences bias my judgement?
- Am I open to consider novel approaches to this problem and willing to learn and study where warranted?

The *intellectually courageous* engineer asks:

- To what extent have I analysed the beliefs I hold that may impede my ability to think critically?
- Do I demonstrate 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 (despite ridicule)?

The *empathetic* engineer asks:

- Do I listen and seek to understand others' reasoning?
- Do I accurately represent viewpoints with which I disagree? Do I accurately represent their views?
- Do I appreciate insights in the technical views of others and prejudices in my own?

Intellectual integrity asks:

- 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 recognise and eliminate self-deception or self-interest when reasoning through engineering issues?

The *persevering* engineer asks:

- 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?

Engineers with *confidence in reason* ask:

- 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?

Engineers with *intellectual autonomy* ask:

- Do I think through technical issues on my own or do I merely accept others' conclusions or judgements?
- Am I willing to stand alone against irrational criticism?

The *fair-minded* engineer asks:

- Am I giving dissenting opinions adequate consideration?
- Has self-interest or bias clouded my judgement?

FUNDAMENTAL ELEMENTS OF THINKING

All thinking entails eight elements, regardless of the domain or subject about which is being considered. Those eight elements provide a framework for analysing either personal thinking or the thinking of others (such as in technical reports or designs). The questions below exemplify those posed by the mature engineering thinker, grouped according to the element of thinking upon which they touch.

Purpose:

- What is the purpose of this design?

Question at hand:

- What product/process will best satisfy the customer's performance, cost and schedule requirements?

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 are being accepted?
- What market/economic/competitive environment is assumed?
- What maturity level or maturation timeline is assumed for emerging technologies?
- What happens if one relaxes or discards an assumption?

Information:

- What is the source of supporting information?
- What information is lacking? How can it be obtained?
- What experiments should be conducted?
- Have all relevant sources been considered?

Concepts:

- What concepts are applicable to this problem?
- Are there competing models?
- What emerging theory might provide insight?
- What available or emerging technologies are appropriate?

Inferences:

- What is the set of viable candidate solutions?
- Is there another way to interpret the information?
- Is the conclusion practicable and affordable?

Implications:

- What are the market implications of the technology?
- Are there disposal or environmental issues?
- What are the implications of product failure?

APPLYING 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, some of the most significant are focused on here.

Specific *clarity* questions in engineering include:

- Are the market/mission requirements clearly stated?
- Have terms and symbols been clearly defined?
- Have the assumptions been clearly stated?
- Do drawings/graphs/photos and supporting annotations clearly portray important relationships?

Specific *accuracy* questions include:

- What is your confidence in that data?
- Has the test equipment been calibrated? How/when?
- How have simulation models been validated?
- Have assumptions been challenged for legitimacy?

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?

Engineers might ask questions of *relevance*, as follows:

- Have all relevant factors been weighed (eg 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 that the customer neither needs nor wants?

Specific *depth* questions include:

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

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 what had been expected (eg hotter, colder, dusty, humid)?

For the engineer, specific *logical validity* questions include:

- Are the design decisions supported by good analysis?
- Are there hidden or unstated assumptions that should be challenged?

Appropriate *fairness* questions include

- Have other points of view been considered (stockholders, manufacturing, sales, customers, public citizens, community interests, etc)?
- Are vested interests inappropriately influencing the design?
- Are divergent views given due consideration?
- Have the environmental/safety impacts been appropriately weighed?

THE MODEL IN ENGINEERING EDUCATION

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

Fostering 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 carried out 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 are 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 wherein an individual or team deficit in intellectual traits hampered team performance. The faculty member or team manager should then collate the vignettes, stripping contributors' names (recognising 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 a technical debrief.

Employing the 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 a newspaper or a single lecture can be decomposed using these 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 coursework.

The eight elements can be introduced to students in several ways. The guide includes a number of templates and examples. The most effective method for 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, eg *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 have been given six to eight minutes to undertake 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 carried out 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 is the source of this insight? Was it theoretical or experimental? What empirical support do we have for this theoretical result?*

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

The value of this practice lies in 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 moving beyond the direct content to wrestling with its implications.

Teaching the Intellectual Standards

An 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 three to four 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 that they have created themselves.

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

Many of us struggled as new faculty trying to identify the most valuable feedback we could provide students. On technical reports, for example, many of us wonder, *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 students' work. Moreover, if the professor's feedback consistently appeals to the standards, either explicitly or implicitly, and holds students to those standards, then students will be more inclined to embrace the standards as the goal that 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 critical thinking vocabulary. They are included in order 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 accidents are commonly dissected for their technical and organisational flaws, it is also illuminating to evaluate the thinking present in these episodes.

CONCLUSIONS

Students' critical thinking implicitly undergirds all the desired skills found in any engineering syllabus. As with other engineering endeavours, models are invaluable in understanding and articulating the connections and interactions of systems and environments. The author applies a model of critical thinking to the mind of the mature engineer, with the goal of helping one understand how to describe one's own thinking and hence better develop the thinking of engineering students. The author also provides a brief list of ideas for directly applying the content to the engineering classroom.

ACKNOWLEDGEMENTS

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