# Critical Thinking in the Engineering Enterprise

**Novices typically don't even know what questions to ask. How can engineering leaders help them catch on more quickly?**

**BY ROB NIEWOEHNER, PH.D.**

In 1990, as a novice test pilot, I was privileged to attend the first flight readiness review for Northrop's YF-23. First flight is a risky event, and several dozen experts from across the country scrutinized the team's preparation. I had thousands of hours in a score of airplanes, but among these grey-beards, I was a novice to the hazards of experimental flight test. I had nothing to contribute and so much to learn.

While impressed with the test team's professionalism, I was even more impressed by the scope and intensity of the questions posed by the gathered reviewers. Most were questions I would never have thought to ask. When I asked a reviewer for the motive behind their question, I invariably heard a story of an airplane damaged, a pilot killed, or a tragedy narrowly avoided. My three days in the back row provided an accelerated education in risk management. I walked away with rich lessons in the questions I should be prepared to answer as a project pilot and questions I would later ask as a program leader.

Research in the traits distinguishing experts from novices shows that experts ask richer questions, questions that are broader, deeper, and more complex, questions that do not balk at obstacles but ferret their way through difficulty (e.g. *How People Learn: Brain, Mind, Experience, and School*). Novices do not know what questions to ask, let alone the answers. Furthermore, novices content themselves with simplistic answers or suspend their inquiry in the face of complexity. How then can we help our young engineers more quickly learn to ask more expert questions of themselves and others? Teach them a critical thinking model.

First we need a substantive definition of "critical thinking," beyond a bumper-sticker phrase for our vague conceptions. I like David Moore's definition from his *Critical Thinking and Intelligence Analysis*:

"Critical thinking is a deliberate meta-cognitive (thinking about thinking) and cognitive (thinking) act whereby a person reflects on the quality of the reasoning process simultaneously while reasoning to a conclusion. The thinker has two equally important goals: coming to a solution and improving the way she or he reasons."

Hence, critical thinking means much more than "logic." Metacognition is vital, meaning "thinking that looks back on itself."

Consider a modern fighter, a system of systems, each of which is overseen by some microprocessor, which constantly monitor the health of each system. Vital systems, such as flight controls, have redundant processors working in parallel. They do not simply process the next aileron deflection, they constantly ask one another, "Do you agree? Are we all healthy?" If one disagrees, it's "voted off." These "health management" technologies have provided much of today's improvement in automotive and aviation maintainability.

Likewise, a robust conception of critical thinking includes not only the process leading from data to a valid conclusion; it must also include the parallel process by which we ask, "Is my thinking healthy?" Critical thinking simultaneously assesses its own quality. Critical thinking certainly entails logic, but it must also entail health management for our thinking.

To illustrate our need, consider the findings of the *Columbia* Accident Investigation Board (CAIB), a masterpiece analysis of high technology organizational behavior. In summary comments, the board described NASA as bereft of deliberate metacognition:

- "NASA is not functioning as a learning organization."
- "[NASA mission managers] were convinced, without study, that nothing could be done about such an emergency. The intellectual curiosity and skepticism that a solid safety culture requires was almost entirely absent. Shuttle managers did not embrace safety-conscious attitudes. Instead, their attitudes were shaped and reinforced by an organization that, in this instance, was incapable of stepping back and gauging its biases. Bureaucracy and process trumped thoroughness and reason."

**Critical thinking certainly entails logic, but it must also necessarily entail health management for our thinking.**

A bright, hard working, dedicated team proved dysfunctional because its organizational culture did not demand that the team consciously monitor the health of its thinking. We may also be leading a bright, hard working, dedicated, dysfunctional team if we've not purposefully taught them how to monitor the health of their thinking. (If our team is high performing, then it's likely we've inadvertently taught them metacognition.)

Our thinking as engineers requires a vocabulary of thinking and reasoning. Engineers love working with conceptual models. The booklet *Engineering Reasoning*, published by the Foundation for Critical Thinking, applies Richard Paul's Critical Thinking Model to the way engineers think. The model's purpose is to improve our thought by aiding in the analysis and evaluation of thought.

The model is not restricted to engineering; its real power is its portability, adapting to any domain of thought. As engineers master the rudimentary skills of critical thinking in the context of engineering, they have really appropriated the skills of life-long learning wherever their professional and personal lives lead them. When they adopt these patterns outside their professional life, their facility is enhanced at work as well.

The goal of Paul's model is the mature thinker, whose thinking skills and ethical dispositions act in concert, as evidenced by "Intellectual Traits/Virtues." The traits are indispensable because they highlight the dispositions necessary to operate well in engineering teams. Reflect, for example, on situations where the performance of your team turned on the presence or absence of any one of these traits. CAIB repeatedly cited NASA for lacking intellectual curiosity, a trait that will be added to future depictions of the model. NSPE's Code of Ethics for Engineers explicitly demands intellectual humility such that we self-consciously restrict our judgments to those domains in which we are truly qualified. Contemplating intellectual virtues causes us to question whether we're acting inconsistent with those desired traits.

The "Elements of Thought" comprise the parts by which we take apart and analyze intellectual work, our own and others. These eight elements are present whenever we think about anything and provide eight basic categories of questions we can ask about any line of reasoning or activity.

1. We should ask questions pertaining to purpose. What is the purpose of this activity, report, article, or meeting? Do the parties have divergent purposes?
2. We should question the question at hand. What question(s) are we attempting to answer? (This is the first question to ask when a meeting begins to wander.)
3. We should clearly recognize the point of view. What point of view does this report express? Are there other relevant points of view that should be considered? Would another point of view provide valuable insight?
4. We should identify and challenge assumptions. What does this author assume? What have we assumed? Are the assumptions valid?
5. We should be clear about our information and data. What do we know? And how do we know it to be true? Is the information current? How might the information be confirmed? What certainty do we attach to individual pieces of information?

### Richard Paul's Critical Thinking Model

**INTELLECTUAL STANDARDS**

| | | |
|---|---|---|
| CLARITY | BREADTH | FAIRNESS |
| ACCURACY | SUITABILITY | DEPTH |
| REVELANCE | PRECISION | CONCISION |
| LOGIC | SIGNIFICANCE | BEAUTY |

MUST BE APPLIED TO

**ELEMENTS OF THOUGHT**

| | |
|---|---|
| PURPOSE | QUESTIONS |
| POINT OF VIEW | ASSUMPTIONS |
| DATA/INFORMATION | CONCEPTS |
| INFERENCE/CONCLUSIONS | IMPLICATIONS |

TO DEVELOP

**INTELLECTUAL TRAITS/VIRTUES**

| | |
|---|---|
| INTELLECTUAL HUMILITY | FAIRMINDEDNESS |
| INTELLECTUAL AUTONOMY | CONFIDENCE IN REASON |
| INTELLECTUAL INTREGRITY | INTELLECTUAL EMPATHY |
| INTELLECTUAL COURAGE | INTELLECTUAL PERSEVERANCE |
| INTELLECTUAL CUROSITY | |

6. We should question the concepts. Is this concept or theory applicable to this situation? Does another theory or principle better explain what we're seeing?
7. We should identify the conclusion. Does the conclusion follow from the information? Are there alternative conclusions that would also fit the data?
8. We should move beyond the immediate conclusion to the implications. What are the implications if the conclusion should prove true? What are the implications if the conclusion should be false?

"Intellectual Standards" are the criteria against which we evaluate the quality of thinking. Thinking professionally entails having command of these standards. You already value these in intellectual work, though you may have thought through only several. The new hire likely thinks in terms of only two standards: "Did I get the right answer?" and "Am I done yet?" When developing our people, we have to help them understand that our business entails so much more than simply being right (accuracy) and logical. We also need their thinking to be clear, significant, concise, deep, and sometimes even beautiful.

Articulating these standards provides a vocabulary whereby young engineers can more rapidly embrace our feedback. Without this vocabulary the new hire may perceive my feedback as random criticism. Instead, I'm deliberate about tagging my feedback to specific standards to which they've been introduced: "This is vague (clarity)." "That's true, but imprecise. Please tighten the precision." "You've oversimplified this interaction (depth)." "This point isn't relevant." "You lost me in unnecessary detail (significance/concision)."

Consequently, critical thinking isn't simply getting the right answer to the problem at hand. Nor is it simply satisfying the rules of logic. We want the best answer, but "best" will not simply mean "accurate"; it will likely also mean clear, precise, relevant, broad, deep, significant, and fair. Furthermore, our failures aren't completely characterized by bad answers to questions; typically our failures can be traced to questions we failed to even ask.

Finally, good thinking will be characterized not only by skills, but also the dispositions to use them. Hence, a model needs to provide concrete guidance on what questions we should ask as well as how to evaluate the quality of the intellectual work that got us to an answer, both to affirm its quality and to identify means by which we can simultaneously improve our thinking processes. The value of a model is helping our junior staff members move more quickly to the scope of questions and depth of thoughtfulness that we may have achieved only after many years.

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