
Lisa Romkey,
Yu-Ling Cheng, University of Toronto
The Faculty of Applied Science and Engineering at the University of Toronto has engaged the question of how to prepare our students for the opportunities, challenges and responsibilities that engineers will face in a rapidly changing global landscape, including the impact of globalization and our responsibilities as global citizens. In considering this changing landscape and the role of the engineer, three themes have been identified for consideration: competitiveness and collaboration; environmental sustainability; and international development. Through a thorough consideration of these themes, and consultation with individuals and groups in education and industry, a list of competencies, defining the global engineer, was formulated:

- Strong technical competency
- Use of creativity in problem solving
- An ability to see engineering projects in the context of multiple disciplines
- A recognition of the business implications of engineering work
- A recognition of the social implications of engineering work
- An ability to work outside of one’s trained discipline
- Adaptability, in type, scope and context of work
- An ability to work with complexity
- Use of a systems thinking approach
- Appreciation and understanding of culture and language
- An ability to use collaboration techniques and software
- Effective oral and written communication
- Knowledge of sustainability practices
- An ability to assess environmental and energy impact across diverse engineering projects
- A well-developed sense of social responsibility and ethics
- Entrepreneurial skills
- A preparation to work with varying levels of resources and in various types of organizations
- Strong critical thinking skills

This paper focuses on the final competency, critical thinking, as a competency that is consistently described as important to the global engineer, but can be difficult to address and challenging to measure. Through a review of existing research, critical thinking is defined and examined in the context of higher education, engineering education and finally global engineering. A preliminary framework to measure a student’s critical thinking in the global engineering context is proposed. It is hoped that this framework is a first step in encouraging discussion about critical thinking in the global engineering context, and providing guidance to engineering faculties on facilitating and measuring global capabilities in their students.
Critical Thinking and the Global Engineer

It is nearly universally acknowledged that the world is becoming increasingly interconnected, interdependent and integrated, and that technology is accelerating at an escalating pace. The interdependence of financial systems and world economies turned a “made-in-America” banking problem into a global economic crisis of historic proportions. Ease of travel allowed avian flu to spread from an isolated remote village in China to cities around the world, and created a health crisis that brought Toronto to a near standstill. Global warming, global political unrest, global epidemics, global poverty – the challenges that future generations of engineers will be asked to address are global in nature. Charles Vest urged universities to "focus on technologies that address the most important problems facing the world; and recognize the global nature of all things technological". The U.S. National Academy of Engineering in "The Engineer of 2020" wrote that "we aspire to a future where engineers are prepared to adapt to changes in global forces and trends and to ethically assist the world in creating a balance in the standard of living for developing and developed countries alike." In addition, as Thomas Friedman famously crystallized, a number of technological innovations have led to the levelling of the competitive playing field, and North American engineers now compete with top talent from around the world.

The combination of globalization trends and accelerating change forecasts a future of unpredictability and complexity that engineering graduates of today will face in their careers and lifetimes. The Faculty of Applied Science and Engineering at the University of Toronto has engaged the question of how to prepare our students for the opportunities, challenges and responsibilities that engineers will face in a rapidly changing global landscape, including the impacts of globalization and our responsibilities as global citizens. Through a process of consultation with stakeholders, three aspects of globalization were identified for consideration: competitiveness and collaboration; environmental sustainability; and international development. In addition, a list of competencies that characterize a global engineer was formulated, which includes: technical competency, creative problem solving skills, interdisciplinarity, recognition of social and business implications, adaptability, communication and teamwork skills across cultural and language boundaries, ability to assess sustainability, ability to work with complexity, and systems thinking and critical thinking skills. This list of competencies overlaps significantly with similar lists produced by others, such as the National Academy of Engineering’s “Engineer of 2020”, Engineers Without Borders Canada’s working definition of a global engineer, the ABET accreditation criteria, and the recently redefined list of accreditation criteria released by the Canadian Engineering Accreditation Board in 2008. It is a staggering list of competencies in engineering students that engineering educators are challenged to teach, help cultivate and assess.

The numerous lists of attributes for global engineers or engineers of the future share a common thread – an increasing emphasis on breadth, professional skills, understanding of the relationship between engineering and society, business and environment, and design and problem solving skills. Implicitly or explicitly, each of these lists includes
critical thinking skills as a core competency for the graduating engineer. Elder and Paul\(^7\) have argued that increasing complexity demands improved thinking skills. In response to the flattening world, Dym has called for increased design and experiential learning – or process and synthesis oriented engineering curricula rather than reductionist analysis\(^6\). And invoking the challenge that engineering graduates will face in a the rapidly changing and globalizing world, Haghighi\(^{15}\) called on engineering educators to take a rigorous, research-based approach to their profession rather than continuing to engage in “an enterprise of methodical guessing” (borrowing a quote from Bertrand Russell). Haghighi also posed a long list of research questions that he called on engineering educators to address.

At the University of Toronto, we made a large number of recommendations for initiatives designed to prepare our students for a globalizing world\(^4\), many of which are now going through the process of implementation. However, we are concerned with the question of how to assess whether these initiatives are successful in achieving the desired attributes in our graduating engineers. In this paper, we explore one of the key attributes – critical thinking. How to achieve this attribute aligns with one of the research questions posed by Haghighi\(^{15}\): “How do you nurture critical thinking, innovation, and ingenuity?”

Although critical thinking is well-accepted as a desired outcome of a global engineer, there is very little information in the engineering education literature to link critical thinking to the engineering context. Except for a recently launched initiative to focus on critical thinking at Indiana University Purdue University Campus\(^5\), we have found very little public dialog among the larger engineering academic community. As a result, there is likely no clear understanding of what critical thinking is or how teaching strategies can be implemented to cultivate critical thinking skills among engineering faculty. In this paper, we hope to demonstrate why critical thinking is relevant to the global engineer, and how we might begin to encourage the development of both critical and global thinkers.

**Critical Thinking: Definitions and Assessment Tools**

Critical thinking is often cited as a desired outcome of higher education, across all disciplines, institutions and many nations. With the rapid proliferation of information, critical thinking is increasing in perceived importance\(^{28}\). However, a lack of clarity about what critical thinking is has lead to confusion about how to teach it and how to assess it; and as a result, university educators typically gravitate to focusing on discipline-based content\(^{25}\), and not the thinking strategies utilized in these disciplines.

In 1990, the American Philosophical Association\(^2\) brought together 46 philosophers, educators and scientists, all experts in critical thinking, and arrived at a consensus view that critical thinking should be conceptualized in two dimensions: skills and disposition. Critical thinking skills are a set of cognitive tools comprised of interpretation, analysis, evaluation, inference, explanation, and self-regulation of information, used in making judgments and decisions. The disposition to think critically is the tendency or willingness to use these critical thinking skills. The Delphi report placed particular
emphasis on the disposition dimension because the body of literature on critical thinking had primarily focused on cognitive tools. Students must be motivated to continually engage in critical thinking before they will employ any cognitive tools they have developed.

Conceptualizations of critical thinking also vary in that some propose critical thinking to be a discipline or skill within itself that does not need to be rooted in the context of another discipline, while others argue that it should be contextualized for strongest retention of the cognitive skills. One related study by Renaud and Murray found that students performed better in a critical thinking assessment when they had the opportunity to practice critical thinking in a subject-specific context. Debate on this question continues as exemplified by Ennis in his comprehensive review on contextualized vs. non-contextualized approaches.

Critical thinking experts have proposed several definitions of critical thinking that are similar to the Delphi report, but reflect these differences in cognitive skills & disposition, and context-based vs. context free. Giancarlo and Facone emphasize that critical thinkers use a core set of cognitive skills in a given context, as do Cooney et al in their review of critical thinking and engineering. Paul and Elder note that critical thinking can be taught on its own, or applied to any subject or problem, and they stress the importance of both cognitive tools and a disposition to use critical thinking and continually reflect on critical thinking. Van Gyn and Ford demonstrate critical thinking as a quality of thinking, characterized by self-regulation that can be applied and assessed within courses or disciplines in higher education.

Most definitions are accompanied by a more detailed set of tools or characteristics that help operationalize the respective definition and use of critical thinking for higher education, and some experts have integrated these characteristics into learner instruments. The California Critical Thinking Skills Test (CCTST) and the California Critical Thinking Dispositions Inventory (CCTDI) are aimed at college students and are designed to measure both the cognitive tools and the students’ disposition to critical thinking – based on the Delphi Expert Consensus Definition of Critical Thinking. Specifically, the CCTST incorporates interpretation, argument analysis, deduction and induction, while the CCTDI measures 7 attributes defined both positively and negatively: truthseeking, open-mindedness, analyticity, systematicity, self-confidence in critical thinking, inquisitiveness and maturity of judgement. Another measurement of critical thinking ability is the Watson-Glaser assessment, an 80-item, multiple-choice test that includes 5 subsets of items: inference, recognition of assumptions, deduction, interpretation and evaluation of arguments. The Cornell Critical Thinking Test has two versions aimed at grade school and early university/college, and includes sections on induction, credibility, observation, deduction and assumption identification. These tools have been used in a variety of research studies on university and college students to determine change in critical thinking over college years, and to correlate critical thinking skills with other attributes including perceived control, academic achievement and study skills.
Surprisingly, research has found that critical thinking doesn’t always correlate to academic achievement or basic study skills, but many suspect that this has more to do with how we choose to teach and assess, with a focus typically on content rather than process. Critical thinking experts tell us that overcrowded classes, over-subscribed students and too much focus on transmission of content translate to an environment where students may not have time to invest in cultivating critical thinking skills. Research on good critical thinking education environments has demonstrated that critical thinking happens when instructors makes a concerted effort to model critical thinking, and use specific instructional methods such as: presenting interdisciplinary problems and approaches, encouraging open-ended discussion, fostering inquiry experiments, ensuring a significant, critical challenge is presented to the learner so that they can authentically practice critical thinking, giving more time for reflection, questioning the epistemology of one’s discipline, and assigning a large number of student-directed and active-learning activities. In discussing critical thinking in the teaching of mechanics, Papadopoulos et al. recognized the need to go beyond content and consider the cognitive tools used in solving mechanics problems, but noted the lack of critical thinking skills in students who are challenged by mechanics problem that are not exact replicas of those seen in assignments or in class. Pithers and Soden described the trend in which a teacher sets problems, demonstrates them to the students, and leaves the student to complete similar problems – and thus develop little if any metacognitive knowledge or skills. This points, once again, to a problem of content vs process, and a need to focus specifically on modelling good thinking processes to students.

Critical Thinking and Engineering Education

Faculty perception of critical thinking in engineering education was highlighted through a thorough study by Scott. The author surveyed a random sample of educators from among over 10,000 ASEE members in the U.S., and compiled results from 251 returned questionnaires that tested 12 hypotheses related to the educators’ view of critical thinking. The surveys probed the faculty members’ beliefs about what attributes are important to the engineering profession, valued by engineering programs, should be possessed by a practicing engineer, and are demonstrated by graduating engineers. The survey also probed the faculty’s beliefs regarding teaching strategies that would be effective at developing thinking skills, and actual teaching strategies they used. Some significant findings were presented in this study. First, there was a significant difference between what the educators believed to be attributes important to a practicing engineer and the profession, and what was actually valued by engineering programs and possessed by graduating engineers. Secondly, while higher order cognitive skills such as logical reasoning, resolving problems and evaluation skills were thought to be valued by both the profession and engineering programs, a lower order cognitive skill, following directions, was thought to be valued more highly by programs than some of the higher order skills. While graduating engineers were thought to be intelligent, knowledgeable, methodical, and rational, they were believed to be less skilled in the key critical thinking attributes of weighing alternatives and questioning assumptions. Finally, the surveyed faculty showed an understanding of the teaching strategies that would promote critical thinking skills consistent with what is known in the general education literature: developing problem-solving strategies.
solving skills, encouraging reasoning, encouraging reflection higher than expanding knowledge, and significantly higher emphasizing procedures. However, while actual strategies used extensively in engineering programs included developing problem solving skills at a high rank, expanding knowledge was ranked even more highly; emphasizing procedures ranked close to problem solving skills, and was significantly higher than encouraging reasoning and encouraging reflection. The picture that emerged was that faculty understood critical thinking skills to be valuable to the profession, recognized a gap between graduating engineers and the “ideal” practicing engineer, understood which teaching strategies would cultivate critical thinking skills, but did not teach in a way consistent with those teaching strategies. Scott speculated that these inconsistencies may be in part due to a lack of engineering specific measurement instruments, and lack of knowledge about how to teach critical thinking strategies specific to the engineering context, and encouraged research in these directions.

The review presented above demonstrates that there is every indication that stakeholders in engineering education believe critical thinking is an important trait to cultivate in engineering students. However, the heavy content in most engineering programs may hinder our ability to encourage the development of explicit critical thinking practices. Coupled with the lack of specific research regarding teaching strategies and their success, the teaching of critical thinking in engineering is rarely explicitly done.

Cooney et al. noted that a recent NSSE survey showed that a smaller fraction of engineering students on their campus perceived that they were engaging in critical thinking than students in other disciplines. The authors proposed that critical thinking needs to become a “brand”; in other words, and as echoed by Scott, we must increase faculty and student awareness of critical thinking for engineering students. Richard Paul and Linda Elder of the Foundation for Critical Thinking, one of the world’s most prominent centres for critical thinking research and dissemination, along with Rob Niewoehner, engineering faculty member at the US Naval Academy, have produced a book specifically for engineering titled “Engineering Reasoning” which includes an emphasis on both cognitive tools and disposition. The book uses the critical thinking model proposed by the Foundation, which includes a set of standards (criteria to evaluate the quality of intellectual work), elements (cognitive tools used to analyze intellectual work) and intellectual traits (which determine the extent to which we use insight and integrity in our thinking).

The model is presented as a tool that can be used for analyzing an engineering document, an engineering design, a problem, model or simulation, or an engineer’s ability to reason or conduct research. The book also uses the model to analyze different disciplines of engineering – for example, identifying the “key concepts” in aerospace engineering or the “implications” of mechanical engineering. A related paper by Niewoehner et al. used the engineering reasoning model outlined above as a tool for evaluating engineering thinking habits and behaviour – and found that the model helped facilitate a more rigorous analysis and understanding of the case study by the students.
In summary, through a review of the various definitions and frameworks for critical thinking, we accept the view that critical thinking involves both a structured set of cognitive tools, and a disposition to be reflective and practice meta-cognition. It is also apparent that to promote critical thinking skills and disposition in students, instructors must be explicit about this goal, model good thinking practice, share a critical thinking framework and provide meaningful opportunities for students to practice critical thinking. The need for critical thinking skills is crucial for the engineers of the future – as they are challenged to address a world of increasing complexity and as they face global competition and global challenges. As well, the global context is one that motivates many students, and as discussed later in this paper, may in fact serve as an excellent vehicle for practicing critical thinking.

A Preliminary Critical Thinking Framework for the Global Engineer

As noted above, critical thinking is often cited as an important skill for the global engineer; critical thinking is proposed as a way the individual can make the best use of information, and make decisions in a complex world. Haghighi states in his guest editorial of the Journal of Engineering Education\textsuperscript{15}, there is now a thorough integration of technology and society which requires understanding technology in a framework that includes environmental, economic, cultural and political differences. We believe that a formal framework in critical thinking can help encourage a thoughtful and successful global engineer.

Van Gyn and Ford\textsuperscript{30} have developed a guidebook on “Teaching for Critical Thinking”, designed to help faculty integrate a framework for critical thinking across various disciplinary courses. Their framework is similar to the other definitions, characteristics and frameworks presented for critical thinking, and in fact was influenced by the work of Richard Paul and the Foundation for Critical Thinking. They include three dimensions in their model: intellectual habits, intellectual deliberations and a reflexive disposition. Intellectual habits are considered “qualities of thinking” that characterize the careful critical thinker. Intellectual deliberations provide the critical thinker with formal ways of thinking, learning and knowing, and are influenced by the particular mode of inquiry or discipline. Finally, a reflexive disposition is the third dimension, and this describes one’s ability to self-regulate and plan ahead when it comes to critical thinking. These dimensions reflect the two main ideas discussed earlier in the paper around critical thinking: cognitive tools, and the disposition for critical thinking.

Using their framework, and what we’ve learned through our research about global engineering, we are proposing a tool for making the critical thinking around global engineering more explicit.
Table 1: Intellectual Habits
Habits demonstrated by a global engineer in any project, activity or discussion

<table>
<thead>
<tr>
<th><strong>Intellectual Curiosity</strong></th>
<th>The global engineer actively seeks perspectives beyond borders, such as knowledge from other regions of the world to apply to the definition and solution of engineering problems. They seek understanding of global issues and challenges beyond their immediate learning and working environment.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Respect for Truth and Reason</strong></td>
<td>The global engineer seeks multiple perspectives when framing a global challenge. They seek evidence to frame and address the challenge relevant to the particular context, such as a particular region, culture or political system.</td>
</tr>
<tr>
<td><strong>Fair-Mindedness</strong></td>
<td>The global engineer seeks pros and cons relevant to a position or engineering solution, using contextualized knowledge (both with respect to a particular community and our global society). They consider the individuals and groups to be involved in the decision or design, and they work with a mindset of social justice; towards a more equitable and just world.</td>
</tr>
<tr>
<td><strong>Open-Mindedness</strong></td>
<td>The global engineer will consider the ideas, opinions and information presented by others and recognize that this may come from a system or context unfamiliar to his or her own. They will acknowledge different ways of knowing, such as regional or cultural knowledge.</td>
</tr>
<tr>
<td><strong>Tolerance for Ambiguity and Complexity</strong></td>
<td>The global engineer is willing to work with ideas that evolve in ways that the traditional engineer is not accustomed to. They understand the limits of one’s knowledge and accept intellectual growth and new methods of thinking through their work.</td>
</tr>
<tr>
<td><strong>Intellectual Courage to Take Position</strong></td>
<td>The global engineer is willing to acknowledge and participate in an engineering challenge, in an international or global context. They take a position on a global issue, even if it isn’t a popular position, if the engineer feels it’s defensible or morally right.</td>
</tr>
<tr>
<td><strong>Intellectual Work Habit</strong></td>
<td>Despite the inherent challenges in working as a global engineer, the engineer persists. They continually strive to develop a better and “whole” understanding needed to work with the respective global engineering challenge.</td>
</tr>
<tr>
<td><strong>Willingness to Engage in Collaborative Inquiry</strong></td>
<td>The global engineer recognizes the inherent collaborative nature of working as an engineer in a global context. They respect knowledge that comes from different cultural and disciplinary contexts, and seeks opportunities to work collaboratively and gain knowledge from others.</td>
</tr>
</tbody>
</table>

Table 2: Intellectual Deliberations
Tools that can be applied to a particular engineering activity, such as a design project

| **Identify the challenge situation or task** | All engineers must engage in problem identification. However, a global engineer must address the additional complexities, such as the consideration of multiple economic, political and cultural systems. |
| **Gather, interpret and understand background information and other evidence** | Upon identifying the challenge, the global engineer must gather technical, political, economic and cultural information necessary to successfully frame the engineering problem, and understand that a comprehensive “data set” is crucial. |
| **Apply thinking strategies relevant to the type of inquiry relevant to the challenge** | The global engineer will consider the vast amount of knowledge needed to engage in global engineering challenges, and will carefully consider strategies to understand and employ this knowledge in the problem-framing, design and solution-generation processes. |
| **Making evaluative judgements among alternatives based on criteria** | The global engineer will consider the unique criteria of global engineering challenges in a consistent and thoughtful manner, and use criteria effectively in the decision-making process. This criteria must satisfy a more complex set of needs; for example, environmental sustainability and economic feasibility across regions and systems. |
| **Provide justification for the conclusion** | The global engineer will provide solutions to a global challenge that is congruent with critical thinking, and justify why this solution is more sustainable than other alternatives. |
Table 3: Reflexive Disposition
The activities that become a part of the global engineer’s mindset and encourage them to continue critical thinking

| Plan ahead for Critical Thinking | The global engineer will actively conceptualize how critical thinking will be used in their work, understanding that they will need to adapt to new ways of working and thinking as a project progresses. |
| Monitor their quality of CT throughout the process | The global engineer will continually monitor their thinking strategies, and will seek new cognitive tools and “ways of knowing” based on their global experiences. |
| Reflect on the strengths and limitations of the use of habits and deliberations in making a judgement | The global engineer will consider the intellectual tools used in this particular project or challenge, and will conceive of ways to think about improvements to thinking and collaborating in the future. |

Actualizing the framework in an engineering curriculum

While recognizing that the framework we have described is preliminary and further input and testing are required, we would like to provide some implementation ideas to help make the framework more concrete. We suggest that the framework should be presented to students and faculty members who strive to encourage the development of global engineers as a “thinking construct for constant consideration”, and actualized in a few key courses or modules in the curriculum. For example, the framework can be provided to students early in their engineering studies, and these students can be encouraged to reconsider the framework, modifying or adding to it as they explore new ideas about the values and skills of a global engineer while moving through their engineering studies. This process can be facilitated through curricular and co-curricular workshops or reflection activities. The framework can also be shared with faculty and others involved with course development, who can be encouraged to find places where these habits, deliberations and a reflexive disposition may be fostered. The following outlines a few curricular opportunities for using the framework:

1. Engineering & Society Courses
Most engineering Faculties offer opportunities for students to explore the impact of technology on society. These courses provide ideal opportunities to engage in activities, such as reflective writing, debate and discussion, about global engineering challenges. At the University of Toronto, a second-year Engineering & Society course includes a module on the role of engineers in international development. Students participate in a lecture on engineering and international development, followed by a discussion seminar and the completion of a reflective writing piece. Some discussion questions that have been used to help students develop an understanding of engineering and international development are:
   - What, in your opinion, is the role of Canadian engineers in international development?
   - How does western bias impact the engineer’s ability to frame a problem while working in a developing country?
What are the lessons learned while working in developing countries that could be applied to engineering in North America?
- How can western engineers better understand the functional, economic and socio-cultural issues related to new technologies in developing nations?
- Consider a candidate technology for introduction to a developing nation. Analyze in terms of its functional, economic and socio-cultural acceptability.

The students’ progress in developing critical thinking skills and the attributes of a global engineer, and the outcomes in addressing these complex questions through both writing and discussion can be assessed and self-assessed using the framework.

2. Engineering Design Activities
Service and global-oriented design projects have become more common in recent years in engineering education. A second-year design course at the University of Toronto asks students to frame an engineering challenge related to one of the millennial development goals. Many of the challenges selected by the students relate to building technology and capacity in unfamiliar countries, providing the students with an opportunity to hone their global engineering skills. The framework can provide both instructors and students with an assessment tool for measuring their use of critical thinking in framing a global engineering challenge.

3. Engineers Without Borders (EWB) activities
Engineers Without Borders has developed a significant presence on campuses across Canada, as a group who encourages students to think about how technology can address issues of poverty worldwide, and provides opportunities for engineers and engineering students to work in developing countries. Similar engineering-focused groups work in institutions around the US and worldwide. Engineers Without Borders student members run curricular and co-curricular workshops for Canadian engineering students that seek to help students understand the complexity of poverty and the role of technology in addressing international poverty. The benefits of these workshops could perhaps be enhanced through the presentation and use of this framework by the facilitators and the participants, and the framework could be enhanced by the outcomes of these activities and the others listed above.

Conclusions & Further Research

It is widely believed in the engineering community that we must use better educational practices to train engineers who are globally-minded and prepared for our complex, interconnected world. Critical thinking has been identified as a key competency of the global engineer, but there is a lack of information on how to teach and nurture critical thinking in an engineering context.

In this paper, we have presented a preliminary framework, originating from a critical thinking framework proposed by Van Gyn and Ford, to encourage the development of critical thinking in the global engineering context. This framework now needs to be shared, tested and refined to reflect a comprehensive formal and self-assessment tool for the global engineer. We also recognize that instructors and Faculties need guidance on
how to best model and teach critical thinking. They also need to develop a better understanding of what it means to educate a global engineer. It is our hope that this framework may be a first step in meeting these goals.

Bibliography


