AC 2012-3360: A HALF BRAIN IS GOOD: A WHOLE BRAIN IS MUCH BETTER

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A Half Brain is Good: A Whole Brain Much Better

Abstract

This paper asserts that engineers could be more creative and innovative, argues that they should be more creative and innovative, and offers ideas on how to enable them to do so. Views of the National Academy of Engineering and various futurists are used to show that the world is experiencing a shift from the knowledge age, with its left-brain foundation, to other more demanding possibilities such as the conceptual, opportunity, wicked-problems, and Grand Challenges ages, which also require strong right-brain capabilities.

The commonality among various future scenarios is the need for whole-brain thinking. Maintaining U.S. global leadership, enhancing national security, achieving personal and organizational success and significance, and functioning effectively as a people-serving profession will increasingly require right-brain individual and group qualities such as adaptability, collaboration, creativity, empathy, entrepreneurship, innovation, synthesis, and visualization to supplement strong left-brain capabilities. Lest there be any misunderstanding, nothing in this paper is intended to detract from the value of left-brain qualities.

After offering a brief brain primer, the paper introduces tools which recognize that, while creative and innovative ideas lie within most of us, we need mechanisms to release them from individuals and from members of teams. Many methods are identified and a few are illustrated. The presentation concludes with ideas on how creativity and innovation knowledge, skills, and attitudes (KSA) might be introduced to engineering students within the context of an already full curriculum.

Keywords – brain, conceptual age, creative, creativity, curricula, Grand Challenges, innovative, innovation, knowledge age, knowledge-skills-attitudes, KSA, left brain, right brain, whole brain, wicked problems age

Introduction

Based partly on the views of various futurists, the world is experiencing a shift from the knowledge age, with its left-brain foundation, to other more demanding possibilities such as the conceptual, opportunity, wicked-problems, and Grand Challenges ages in which those who achieve success and significance will exhibit strong left- and right-brain capabilities. The common thread among various future scenarios, as explained in this paper, is the need for whole-brain thinking. Maintaining U.S. global leadership, enhancing national security, achieving personal and organizational success and significance, and functioning effectively as a people-serving profession will increasingly require right-brain individual and group qualities such as adaptability, collaboration, creativity, empathy, entrepreneurship, innovation, synthesis, and visualization to supplement strong left-brain capabilities. However, while we need to further engage our right hemispheres we must also continue to value and develop left-hemisphere qualities.

Engineers could be more creative and innovative and they should be more creative and innovative given the preceding changes. Fortunately, individual engineers and teams composed of engineers and members of other disciplines can be equipped with many useful tools, many of which are listed and three of are described in this paper. These methods recognize that, while creative and innovative ideas lie within most of us, we need mechanisms to release them for the benefit of individual and members of teams. The paper concludes with ideas on how creativity and innovation knowledge, skills, and attitudes (KSA) might be introduced to engineering students within the context of an already full curriculum.

Definitions

The nouns creativity and innovation and the related verbs, create and innovate, have many and varied definitions and interpretations. This observation follows from a literature search[1,2,3,4] and conversations with colleagues. Accordingly, for the purpose of this paper, I offer these definitions:

- Create: Originate, make, or cause to come into existence an entirely new concept, principle, outcome, or object. Examples: Small Post-it notes and Velcro.

- Innovate: Make something new by purposefully combining different existing principles, ideas, and knowledge. Examples: Large Post-it notes and Gutenberg's reusable type printing press

The Brain: A Primer

By understanding the brain basics, we are more likely to appreciate the desirability of further engaging our right hemispheres and, therefore, realizing the creative and innovative power of our whole brain. As noted by author Robert Cooper:[5] "It's an amazing instrument, your brain, but it's up to you to see that it plays the tune you want." Playing that tune requires a basic understanding of how the instrument works. Consider an analogy. You want your car to get better gas mileage. Therefore you study and experiment with selected aspects of your car such as tire pressure, engine tuning, and use of the accelerator.

The human brain is about the size of a small head of cauliflower and weighs about three pounds.[6] It is very soft, tan-gray on the outside, and yellow white on the inside.[6,7] The brain contains 50 to 100 billion nerve cells, called neurons, which can receive and send electrochemical signals.[6,7] Each neuron has an average of 10,000 connections with other neurons.[8] The human brain[6]:

- "controls body temperature, blood pressure, heart rate, and breathing;

- accepts a flood of information…from…various senses (seeing, hearing, smelling, tasting, touching, etc.);

- handles physical motion when walking, talking, standing, or sitting, [and does most of this without our having to think about it]; and

- lets [a person] think, dream, reason, and experience emotions."

Hardwiring of the brain is a metaphor suggesting that the brain is like "computer hardware, with permanently connected circuits, each designed to perform a specific, unchangeable function."[9] While this view of the brain was first proposed in the 17th century,[9] and may still find adherents, a newer, more likely alternative view of the brain is that it has the property of neuroplasticity.[10] As explained by Norman Doidge, author of *The Brain that Changes Itself* [9] *and* a supporter of the neuroplasticity view, "Neuro is for neuron…Plastic is for changeable, malleable, modifiable."

The brain, when stimulated, can grow. According to Doidge,[9] "mental training or life in enriched environments increases brain weight…Trained or stimulated neurons develop 25 percent more branches and increase their size, the number of connections, and their blood supply." He goes on to note that "these changes can occur late in life, though they do not develop as rapidly in older animals as in younger ones." Neurons form in our minds until the very end of life. As noted by Doidge, "The idea that the brain is a muscle that grows with exercise is not a metaphor."

In summary, the theory of neuroplasticty means that "thinking, learning, and acting actually change both the brain's physical structure (anatomy) and functional organization (physiology) from top to bottom."[10] The significance of neuroplasticity, as summarized here, is the suggestion that we engineers, as students, faculty, and practitioners, can change the way we think—change our brains. We can enhance understanding of our brains, engage more of our brains, expand our brains, and, as a result, become more creative, innovative, and effective consistent with our rapidly-changing world.

When the brain is viewed from above, it is seen to have symmetrical left and right halves or hemispheres connected by white communication fibers called the corpus callosum.[6,7] Each of the brain's hemispheres interacts with the opposite side of the body. This is referred to as lateralization which means that the left side of the brain interacts with the right side of the body and vice-versa. Therefore, just as the two hemispheres are symmetrical in appearance, they are also largely symmetrical in function.

There are exceptions, however, to functional symmetry. These exceptions are very relevant to this paper and are presented in Table 1.[11] They have been revealed, in part, by observation of individuals who have undergone surgical transection of the corpus callosum thus disconnecting the two hemispheres.[10] Although few in number, the exceptions to functional symmetry are relevant to this paper.

Table 1. With respect to how we think, the brain's left and right hemispheres differ markedly.

LEFT HEMISPHERE	RIGHT HEMISPHERE
Verbal	Nonverbal
Analytic	Synthetic
Symbolic	Actual
Abstract	Analogic
Temporal	Nontemporal
Rational	Nonrational
Digital	Spatial
Logical	Intuitive
Linear	Holistic

Why Creativity and Innovation and Why Now?

From the beginning of recorded history and all over the earth, individuals we would now label engineers have met the basic needs of communal society.[12,13,14,15] While that role will remain essentially the same, the stage on which that role is played will change dramatically. The following sections explore that new stage with the hope that we will leverage the education and early career experience of tomorrow's engineers so that they can fulfill their role on that new stage.

The Grand Challenges for Engineering

The National Academy of Engineering (NAE) identified 14 grand challenges for engineering in the 21st Century.[16] The names of the challenges are listed in Table 2; note their breadth and implied depth.

Table 2. The National Academy of Engineering presents broad and deep challenges to the engineering profession.

Grand Challenges for Engineering
• Make solar energy economical
• Provide energy from fusion
• Develop carbon sequestration methods
• Manage the nitrogen cycle
• Provide access to clean water
• Restore and improve urban infrastructure
• Advance health informatics
• Engineer better medicines
• Reverse-engineer the brain

- **Prevent nuclear terror**
- **Secure cyberspace**
- **Enhance virtual reality**
- **Advance personalized learning**
- **Engineer the tools of scientific discovery**

Judging from the following NAE statement,[16] the Academy is confident that the engineering community will rise to the challenges: "The world's cadre of engineers will seek ways to put knowledge into practice to meet these grand challenges. Applying the rules of reason, the findings of science, the aesthetics of art, and the spark of creative imagination, engineers will continue the tradition of forging a better future." Note that, according to NAE, meeting the challenges will require that tomorrow's engineers bring many and varied qualities to the table, including the "aesthetics of art" and "the spark of creative imagination."

After the Knowledge Age: The Conceptual Age?

Advanced societies have progressed through the agricultural and industrial ages and into the knowledge age. Daniel H. Pink[17,18] argues that the present knowledge worker age, which followed the agricultural and industrial ages, is gradually being superseded in the U.S. and other advanced countries, as illustrated in Figure 1, by what he calls the conceptual age.

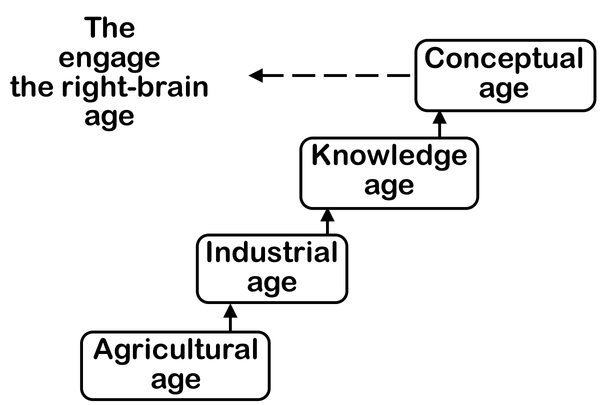


Figure 1. The knowledge age may be superseded by the conceptual age in which a premium is placed on original ideas and concepts

What does Pink mean by the conceptual age? Recognize that the root word is conception which suggests a new, beginning, or original idea. Pink says the conceptual age is "an era in which mastery of abilities that we've overlooked and undervalued" will be required.[18] He says that these increasingly-valued abilities emanate from the brain's right hemisphere and include visualization, innovation, creativity, synthesis, empathy, and helping people find meaning.

Functioning effectively in the knowledge age requires primarily left-hemisphere or left-brain abilities. Engineers and other technical professionals are prime examples of knowledge workers. They logically and sequentially collect and analyze data, calculate, and design to meet requirements. Also relying heavily on their left hemispheres, accountants prepare tax returns, lawyers research lawsuits, radiologists read diagnostic data, software experts write code, and stockbrokers execute transactions.

According to Pink, left-brain abilities will be necessary, but not sufficient, in the conceptual age. A half a brain will be necessary, but not sufficient. A whole brain will be needed if one is to succeed, especially in the U.S. and other advanced countries. Why? Because work that "can be reduced to a set of rules, routines, and instructions," the functions of the left brain, is "migrating across the oceans…Now that foreigners can do left-brain work cheaper, we in the U.S. must do right brain work better."[18] Fiber-optic cables and a growing number of ambitious, smart, and English-speaking workers in India, China, the Philippines, Singapore, and other countries facilitate this outsourcing process.

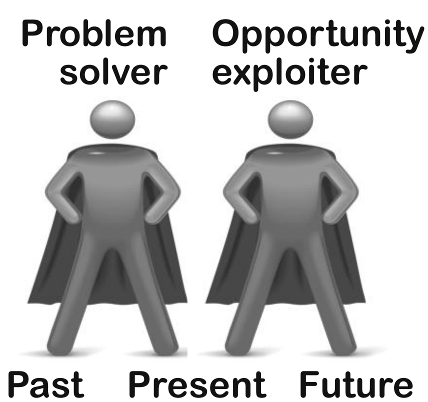
Accordingly, if Pink is correct, in the conceptual age leading edge engineers will focus less on solving problems and more on finding and developing opportunities. In similar fashion, accountants will serve more as financial advisors, lawyers will concentrate more on convincing juries and mastering the nuances of negotiation, and stockbrokers will become financial advisors to help people realize their dream.

After the Knowledge Age: The Opportunity Age?

Futurist John Naisbitt[19] offers a related view of the future. He states: "When you're looking for the shape of the future, look for and bet on the exploiters of opportunities, not the problem solvers." He goes on to claim that individuals tend to embrace one of two poles, stasis or dynamism, stability versus evolution, predictability or surprise.

As shown in Figure 2, Naisbitt suggests that problem solvers tend to have one foot in the past; it's the origin of the problems they solve. In contrast, opportunity exploiters, while living in the present, have one foot in the future; it's the place of promise.

Figure 2. Problem solvers tend to look backward while opportunity exploiters are inclined to look forward.



To restate, in a different way, a point made in the preceding discussion of Pink's ideas, most professions focus on solving problems and do a superb job. Examples are engineering, law, and medicine. Most engineering curricula emphasize problem solving and, to a lesser extent, problem prevention. Rarely, especially at the undergraduate level, would a student be explicitly exposed to finding and pursuing opportunities, as espoused by Naisbitt.

Engineers solve well-defined problems and do it very well. This admirable ability is learned, in large part, during engineering education. This teaching-learning method is also very left-brained. For example, it is linear: present theory, discuss theory, assign problems which use the theory to reach a solution, provide students with everything needed to understand the problems, use theory to solve problems, get "the answer," and discuss how the successful students got the answer.

I support the preceding method of learning theories and applying them to solve problems. After all, understanding theories is essential to engineering practice and problem solving is an important aspect of engineering. However, engineers can also perform other functions, besides problem solving, such as creatively and innovatively identifying and pursuing opportunities.

After the Knowledge Age: The Solving Wicked Problems Age?

John Kao,[3] teacher, consultant, and innovation expert, is concerned that the U.S. may feel smug about its pre-eminence thinking. That is, he questions the idea that other countries will continue "to settle for being followers, mere customers, or imitators of our fabulous creations" and he asserts that "innovation has become the new currency of global competition as one country after another races toward a new high ground where the capacity of innovation is viewed as a hallmark of national success." He goes on to say that "what's at stake is nothing less than the security of our [U.S.] nation."

Kao's book,[3] *Innovation Nation: How America Is Losing Its Innovation Edge, Why It Matters, and What We Can Do To Get It Back,* diagnoses the U.S. situation, describes innovation best practices from around the globe, explains how innovation works at the national level, and proposes a U.S. strategy. That strategy is to become what he calls an Innovation Nation, that is, "a country with a widely-shared, well-understood objective of continuously improving our innovation capabilities in order to achieve world-changing goals." Clearly, Innovation Nation would, as a matter of policy, begin to teach creativity and innovation to its children and young people or, to use Kao's words, "fix the U.S. education system."

Kao envisions "a concentrated application of our vast resources to innovate on a huge scale for human benefits." He wants America "to be in the wicked problems business." By this, Kao means taking on global issues such as "climate change, environmental degradation, communicable diseases, education, water quality, poverty, population migration, and energy sufficiency." Creative and innovative solutions to the wicked problems are the key to making the most consequential breakthroughs of the 21st century;

these solutions will generate "an enormous amount of social and economic value" and enable Innovation Nation, that is, the U.S., to do good and do well.

Implications for Engineering Education?

Assume, for purposes of discussion, that Pink,[17,18] Naisbitt,[19] Kao,[3] and NAE,[16] as well as others such as Peterson[20] and Blij,[21] who are not discussed here, are collectively correct in stressing that maintaining U.S. global leadership, enhancing national security, enjoying organizational vitality, and achieving personal professional success and significance will increasingly require personal and group qualities such as adaptability, collaboration, creativity, empathy, entrepreneurship, innovation, synthesis, and visualization. If this assumption is correct and is coupled with the traditional people-serving function of engineers, it has have serious implications for engineering education. Are we offering our students the opportunity to acquire the KSA that will be needed to serve while thriving, or at least surviving, on the global stage as described above? Hopefully, engineering students are being prepared for the way engineering will be practiced in the 21st Century, not the way it was practiced.

Engaging the Right Brain Because a Whole Brain Would Be Better

Recall the assumption stated in the previous section and the personal and group qualities identified. Those are left brain qualities stand in contrast with left-brain qualities such as verbal, analytic, symbolic, abstract, temporal, and linear. Based on our understanding of the human brain, this means that individual and group success will require further development of right-brain capabilities while at least maintaining left-brain capabilities; that is, enhancing left-mode thinking by developing more right-mode thinking.

Author and artist Betty Edwards[11] says this about the U.S. K-12 and beyond educational system: "Most of our educational system has been designed to cultivate the verbal, rational, on-time left hemisphere, while half of the brain of every student is virtually neglected." She elaborates on her statement noting that while we will find a few art, shop, and creative writing K-12 classes, we are unlikely to find courses about imagination, visualization, perception, creativity, intuition, and inventiveness.

Might the preceding also generally characterize engineering education? This is generally the case in given typical engineering curricula. Betty Edwards succinctly said it this way: "Half a brain is better than none: a whole brain would be better." Accordingly, discussion of possible ways to discover and enhance right-brain capabilities in engineering education and in practice is warranted. Let's explore more use of the right hemisphere—while not taking away from the value of the left hemisphere.

Whole-Brain Tools

Fortunately, many methods are available to assist individuals and groups in engaging both "cranial" hemispheres so that they can more creatively and innovatively address issues, solve problems, and pursue opportunities. When faced with an issue, problem, or opportunity, we typically develop some options, explore their pros and cons, make a decision and then act on it as illustrated in the upper part of Figure 3.

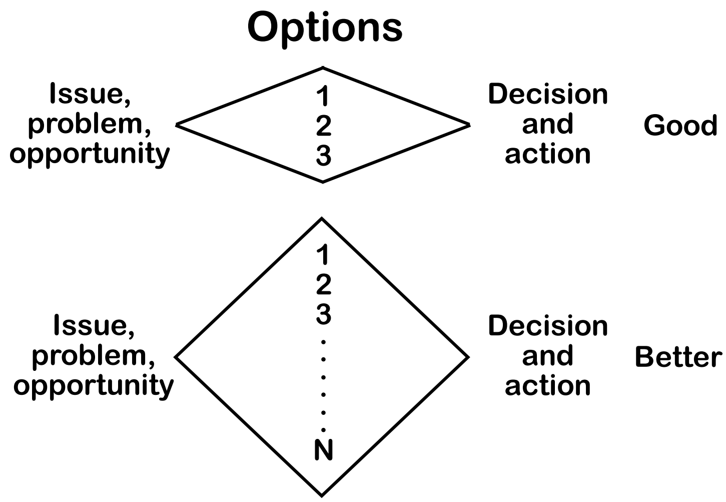


Figure 3. More options tend to yield better decisions.

The quality of our decision is likely to be better when we have more options, more ideas, as suggested by the lower part of the figure -- especially if the ideas are highly-varied. Scientist Linus Pauling said "the best way to have a good idea is to have lots of ideas." This early on, more-is-better concept, applies whether we are striving to define an issue, problem, or opportunity or we are endeavoring to resolve the issue, solve the problem, or pursue the opportunity.

The commonality of the available tools described or named in this paper is being able to stimulate individuals and, more powerfully, a group, such as a planning, design, research, marketing, or other project or task team, to think more deeply and widely—to generate more ideas. More specifically, the methods in the toolbox stimulate additional right-brain use to complement left-brain activity, yielding more creativity/innovation, rather than relying only on what athor Gerard Nierenberg[4] calls "accidental creativity." These tools facilitate intentional creativity and innovation by engaging both cranial hemispheres. They stimulate both hemispheres and synergism between them. Some of the methods presented here build on the principle that a problem well-defined is half solved and others offer ways to envision many, diverse options and then select among them.

Use of the toolbox recognizes that, while creative/innovative ideas lie within most of us, we need mechanisms to release them; we require creativity and innovation KSA. "We know where most of the creativity, the innovation, the staff that drives productivity lies," according to former GE Chairman Jack Welch, "in the minds of those closest to the work."

Table 3 lists the names of the tools that I have discovered and many of which I have used. The methods are listed alphabetically to dispel any notion of preference or priority. Three of the tools – borrowing brilliance, fishbone diagramming, and mind mapping -- are discussed here as a means of suggesting the variety and usefulness of the toolbox. However, this paper is not intended to dwell on the tools. Refer to the sources indicated in the table for detailed discussions of the methods.

Table 3. Tools, such as these, stimulate whole-brain thinking.

Biomimicry[22]	**Pareto Analysis[24]**
Borrowing Brilliance[23,a]	**Challenges-first meetings[24,27]**
Brainstorming[24]	**Process Diagramming[24]**
Delphi Technique[1]	**Puzzles[28]**
Fishbone Diagramming[24,a]	**Six Thinking Caps[29]**
Freehand Drawing[25]	**Stimulating Environment[26]**
Medici Effect[26]	**Swiss Army Knife[30]**
Metrics[24]	**SWOT[24]**
Mind Mapping[24,a]	**Take a Break[24]**
Multivoting[24]	
New Points of View[4]	
Ohno Circle[24]	

a) Discussed in this paper

Although highly-varied, these tools share three practical common features. They are easy to understand, take little time to apply, and they work. Their value does not reside in their sophistication but rather in their ability to engage the whole mind of individuals and, even more powerfully, of members of teams or groups.

Borrowing Brilliance

Engineer, entrepreneur, and author David K. Murray[23] argues, in his book *Borrowing Brilliance*, that the most effective path to creativity-innovation is mixing and matching the concepts of others, especially when the others are from disparate fields. He repeatedly suggests, presumably tongue-in-cheek, that his approach is a game, bordering on stealing. While author Murray may have some fun with his "borrowing brilliance" terminology, all of us who have conducted scholarly research know that we build on the work of—stand on the shoulders of others. We also recognize that scholars carefully cite their sources.

Moving on, D. K. Murray offers informative examples of creative-innovative efforts that built on the work of others. Johannes Guttenberg, in designing the reusable type printing press in 1452, borrowed from woodblock printing, which had been used for hundreds of years; weapon and coin forging; and the screw press process used by winemakers and olive oil producers.[23,31]

Charles Darwin, in creating his evolution theory and publishing *On the Origin of the Species* in 1859, borrowed from biologists who catalogued species, except while biologists catalogued differences in species, Darwin catalogued similarities. Darwin also borrowed from geologists and, in particular, the English geologist Charles Lyell who, in 1830, published *Principles of Geology*. His book argues that geological features represented the cumulative effects of various processes such as wind, water, and precipitation occurring over long periods of time. This stimulated Darwin to think about the effect of "long periods of time" on biology.[23]

Henry Ford, in developing the moving assembly line from 1908 to 1915, borrowed from meat packing companies. They "used a moving hook and conveyor system to disassemble a cow." He reversed this and created a process to assemble a car. That is, Ford created the first version of today's very sophisticated automobile manufacturing process which consists of cars—being assembled, not disassembled—as they move past stationary stations where workers and machines add value to each evolving car.[23]

What issue, problem, or challenge are you facing that might be resolved using a process or approach from some very different discipline or specialty?

Fishbone Diagramming

This method, which is also called a cause and effect analysis or the Ishikawa Analysis,[32,33,34] provides a systematic way to thoroughly identify widely-varying possible causes of a problem. Assemble a diverse group, provide background, pose the problem, and construct the fishbone diagram.

Assume that an engineering project team is studying a recently constructed stormwater detention facility that seems to have failed to protect downstream properties during a large rainfall event. Begin constructing the fishbone diagram, as shown in the Figure 4, by drawing the head.

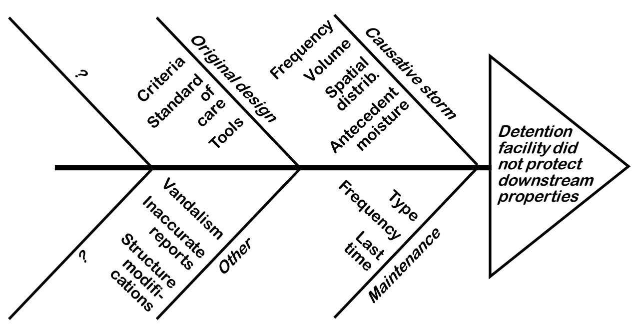


Figure 4. The process of drawing the fishbone diagram encourages broad and deep thinking about the possible causes of a failure.

Then collaboratively identify possible "bones," that is, categories of possible causes of failures such as causative storm, maintenance, the original design, and other. Then creatively detail each "bone," make judgments as to the likely cause or causes of failure, and develop an action plan.

Mind Mapping

Mind mapping[26,35] or clustering[36] is a tool that helps an individual or team address an issue, solve a problem, or pursue an opportunity. It is effective in defining the issue, problem, or opportunity and then in identifying potential was to resolve the issue, solve the problem, or pursue the opportunity.

Consider Figure 5, a mind map developed by a group of four. They were addressing a problematic pond in a residential area. A half-hour mind mapping process was used to define the problem. For the purpose of sharing the result, the subject of the mind map is not important other than to say that, at the outset, the topic being addressed was poorly defined in that the four individuals had different perceptions. The important aspects are the resulting format and the process used to create it.

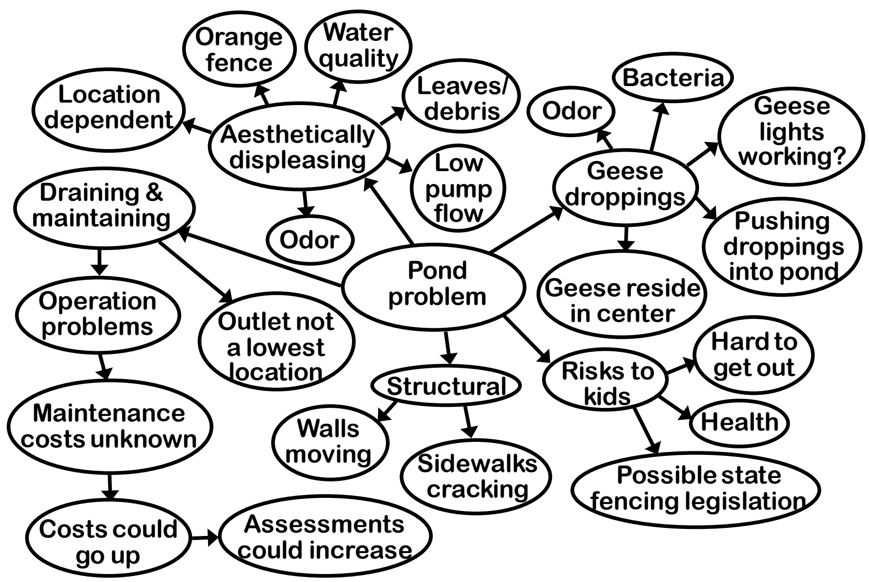


Figure 5. Preparing this mind map enabled group to define a problem.

To get started, state and show the topic which, as indicated in Figure 5, was “Pond problem” Then ask each participant, “what does this make us think of?” or “what comes to mind?” Whatever “pops” into anyone’s mind, and is shared, is added to the mind map using ovals and connecting them with arrows. My experience in using mind mapping is that, once I or a group gets started, a flood of ideas quickly appears. And soon, very soon, a large mind map or cluster appears. While doing this, do not be judgmental of anything. If it “appears” it gets mapped.

By the way, draw by hand, don’t use software. Hand drawing is uninhibited, will enhance spontaneity, and engages the right hemisphere of your brain.[26] As shown in Figure 5, mind mapping identified five problem areas and elaborated on each of them. As soon as the mind map was finished, the group turned to a discussion of possible solutions. The premise of this exercise is that a problem well-defined is half solved.

Clearly, this tool can be used in a variety of situations. For example, using mind mapping, a team of graduate students identified 14 potential uses, in addition to safety, for highway median barriers. Another student team used mind mapping to list structural and non-structural ways to quickly and temporarily flood-proof a highly-vulnerable manufacturing plant that was threatened with flooding because of melting of unusually heavy watershed snow cover.[37]

Mind mapping is an effective means for generating ideas, whether performed individually or by a group, because:

- It can be done quickly in real time by simply drawing on an individual's knowledge and experience, or the combined knowledge and experience of members of a group.

- No preparation is required other than to choose the topic and then select participants who are very diverse in terms of characteristics such as knowledge, skills, attitudes, and experiences.

- Once the process starts, ideas flow and one idea leads to another. The process is all about generating ideas for later consideration.

- The process is non-linear in that it does not require one item to logically follow another in step-by-step fashion, and, as a result, many and highly-varied ideas are generated. Stated differently, the process, whether done by an individual or a group, engages both hemispheres of participant's brains.

Fitting Creativity/Innovation into an Already-Full Curriculum

Traditional engineering curricula emphasize mathematics, science, and analysis and, as such may be categorized as left-brain oriented. Traditional curricula also include design and its creative-innovative aspects which draw on the right-brain and left-brain.

However, as shown in the upper part of Figure 6, that design typically occurs near the end of a student's academic program and comprises a very small part of the program.[37] Please note that I am referring to traditional engineering curricula and I am basing my comments on U.S. practice. There are curricular exceptions—engineering programs that embody design and other whole-brain educational activities earlier if not throughout the undergraduate program. Some are noted later in this paper.

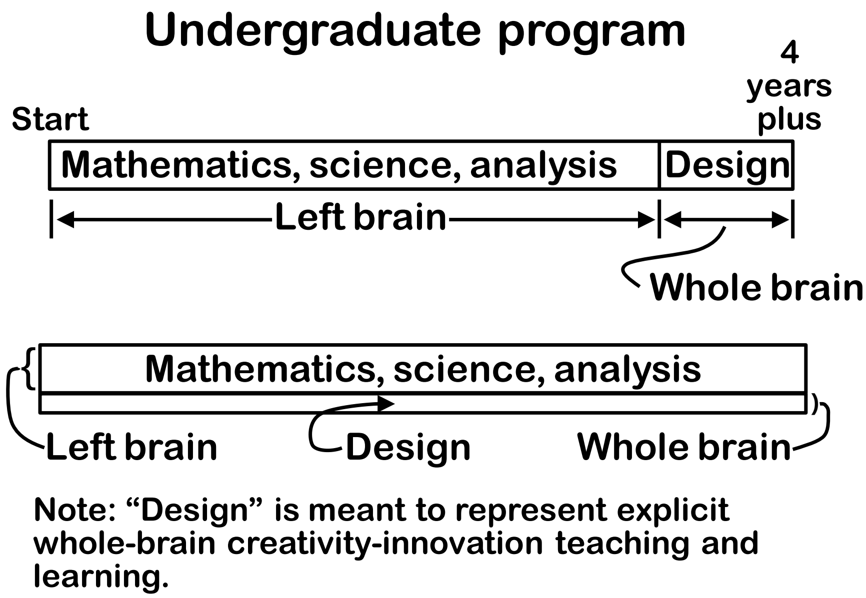


Figure 6. With a strong whole-brain approach, design appears in all years of a curriculum.

Deferring design, and more specifically, creativity and innovation, until the end of an academic program may cause these two problems:[38]

- Students lose interest in engineering. Young people who are drawn to engineering because they view it as being design-oriented may lack the motivation to continue in the program that appears to be analytically-oriented. "I have seen again and again civil engineering students who were bright-eyed and enthusiastic as freshmen," according to instructor Edward Allen,[39] "turned into dull, defeated calculation drudges by four years of math only courses in engineering." Somewhat more gently, Richard Felder[40] observes "It would seem to be our responsibility to produce some creative engineers – or least not to extinguish the creative spark in our students."

- Being steeped in left-brain studies for three plus years and then being asked to also draw heavily on the right-brain—a very different mode of thinking—may be difficult. Heavy, that is, multi-year emphasis on analysis may impair students' creative-innovation abilities.

We have an alternative to the traditional heavy front-ending of analysis (left-brain). As shown in the lower part of Figure 6, design (whole-brain) could appear in all years of the curriculum. More specifically, include conceptual design in the first year. Follow this with preliminary design and detailed design in the remaining years. The left and right hemispheres are explicitly engaged throughout all years of the curriculum.

Now back to the principal purpose of this section which is to answer the question: How can we fit creativity and innovation into an already full curriculum? How can we "stuff" even more into that undergraduate program? Allow me to offer some preliminary curricular and curricular-related ideas. Perhaps some of these will resonate with you and enable you, and perhaps colleagues, to experiment with introducing more creativity-innovation into your curriculum. See also the varied ideas, many of which go way beyond curriculum, offered by T. Arciszewski.[26]

1. Learn from others such as the following:

- George Mason University: Tomasz Arciszewski,[41] a member of the Department of Civil, Environmental, and Infrastructure Engineering, teaches the undergraduate course Introduction to Design and Inventive Engineering and the graduate course Design and Inventive Engineering

- Purdue University: Connolly and Sadowski[42] describe the use of 10-minute exercises (also called brain teasers and puzzles) at the conclusion of a weekly lecture in first and second freshman computer graphics course. The intent was to provide students with "a stepping stone to more involved creativity developing exercises and projects and resulting in early, confidence-building success in the problem solving area." As a supplement to the eight brain teasers or puzzles presented in the paper, see the Restak and Kim book *The Playful Brain.*[28]

- Stanford University: The mission of Stanford University's d school (for design school) or, more formally, the Hasso Plattner Institute of Design, is to enable students to be creative. Graduate students from all of Stanford divisions take courses. "Multi-disciplinary pools of teachers then immerse them in a system of innovative thinking, with specific goals for solving practical problems."[43] Key d school elements include a highly-flexible physical environment, interdisciplinary teams, and emphasis on constructing prototypes, as crude as they may be, in keeping with the "build to think" philosophy. According to David Kelley, the d school's founder and leader, products created by the six-year old institute have already positively impacted "millions of lives," especially in the developing world.[43]

- University of Wisconsin-Madison: The College of Engineering annually sponsors Innovation Design, a competition open to all university undergraduates. The event is supported by the one credit inter-engineering course "Process Innovation: Conception, Selection, and Commercialization of Ideas."[44]

- And, farther from home, study the education creativity and innovation efforts in nations such as Denmark, Finland, and Singapore.[3]

2. If you are experimenting with or have developed ways to explicitly include creativity and innovation in an engineering program, share your lessons learned by means such as presenting and publishing papers and conducting workshops.

3. Keep in mind a point made earlier in the tools section of this paper mainly that the tools share this practical common feature: They are easy to understand, take little time to apply, and they work. Accordingly, they can be introduced and used with little effort in courses.

4. Leverage your first year Exploring Engineering, Introduction to Engineering, or similar course, during which you have student teams solve well-defined design problems. Briefly explain brainstorming and multivoting and ask each team to use these collaboration methods to more fully utilize their collective minds.

5. During a second or third year course, in which each student is assigned a research paper, show how mind mapping is used to engage both hemispheres in quickly identifying possible content.

6. Within the capstone course, present and ask students to use the open-ended fishbone diagramming to determine the cause of a problem followed by the "as is" and "to be" process diagramming and/or borrowing brilliance to seek solutions to it.

7. Share creativity-innovation stories such as the creation of Velcro. It was "Invented in 1948 by the Swiss electrical engineer George de Mestral."[45] This hook-and-loop fastener is made of Teflon loops and polyester hooks. Velcro is now headquartered in Manchester, New Hampshire. Mestral was returning from a hunting trip with his dog, noticed burdock burrs (seeds) on his clothes and on his dog's fur, examined the burrs under a microscope, and noted many "hooks" that caught on anything. "He saw the possibility of binding two materials reversibly in a simple fashion…Originally, people refused to take him, and the idea, seriously…"[45] He worked 10 years to "create a mechanized process that worked."[45] Velcro, the word, is a coined word, that is, a combination of two other words: he French words velour, meaning fabric with a soft nap, and crochet, that is, needlework in which loops of thread or yarn are interwoven with a hooked needle.[45]

8. Arrange for inventors and entrepreneurs to speak in classes. Suggest that student groups, such as student chapters of professional societies, invite inventors and entrepreneurs to speak at their meetings.

9. Interview artists and other "creative" types. Ask about the "source" of their "creativity," assuming that they tend to think that way. Another possibility is that creativity is not involved. They simply see more by means of their right brains and draw, paint, or otherwise present what they see.

10. Study the origins of an admired product/facility/process/service. Engineering students and faculty can learn more about being creative and innovative in project management and other aspects of professional work by studying creative/innovative endeavors. Ask members of each student team to share views of things or processes they admire. Don't limit the search to topics to those within a particular engineering discipline. Then select one thing or process and determine the following:

- Who (individual or team) is credited with the original idea?

- What motivated the creative/innovative effort, that is, what were the circumstances? Stated differently, what issue, problem, or opportunity was being addressed?

- How did the creative/innovative idea arise? For example, did the individual or team follow some systematic process or did the idea simply "appear?"

- What was needed (money/expertise/legal process/testing/elapsed time) to implement the creative/innovative idea?

I asked student teams to do the preceding and was surprised at the range of topics they selected (e.g., the ballpoint pen and the Japan bullet train) and informed and encouraged by what they learned.

11. Participate in student creativity-innovation competitions. For example, the Biomimicry Institute sponsors the annual (third annual in 2011) Biomimicry Student Design Challenge which is open to interdisciplinary undergraduate-graduate teams. The 2011 theme was Biometric Solutions to Energy Efficient Challenges and the winning entry was to receive a $5000 prize.[22]

12. Raise awareness during "co-op," internships, summer jobs, and part-time jobs. Encourage students, while participating in these activities to look for creative and innovative developments and determine the extent to which they are valued and encouraged. How important is organizational culture?

13. Conduct a controlled experiment. For example, form a hypothesis such as engineering students will perform better academically if they learn and apply creativity-innovation tools or engineering students will be more creative-innovative if they participate in visual arts. Conduct the experiment (e.g., using parallel sections of the same course), analyze the data, and draw conclusions. Somewhat ironically this would be a classic left-brain study of a right-brain dominated hypothesis.

14. Assess the results of explicitly including creativity-innovation in the curriculum by determining the impact, if any, on:

- Student and faculty motivation and morale

- Student recruitment and retention

- Alumni success and significance

- Strengthened and/or expanded relationships with industry

- Funding, equipment, and other resources received from external sources

- Image and reputation of the department, college, and/or institution

Summary of Key Ideas

As the world moves beyond the knowledge age into new, even more demanding times such as the Grand Challenges, conceptual, opportunity, and wicked problems ages, U.S. engineers will need to be more creative and innovative. Maintaining U.S. global leadership, enhancing national security, achieving personal and organizational success and significance, and continuing the profession's people-serving function will increasingly require right-brain individual and group qualities such as adaptability, collaboration, creativity, empathy, entrepreneurship, innovation, synthesis, and visualization to supplement engineers' strong left-brain qualities such as verbal, analytic, symbolic, abstract, temporal, and linear. Explicitly providing students and the practitioners they become with a whole-brain capability may once have been viewed as "frosting on the cake;" now it may be the cake.

Many easy to learn and use tools are available to engineering faculty and students which recognize that, while creative and innovative ideas lie within most of us, we need mechanisms to release them from individuals and from members of teams. We can offer creativity and innovation knowledge, skills, and attitudes (KSA) to engineering students within the context of an already full curriculum.

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