LESSONS FROM ENGINEERING PHILOSOPHY

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Abstract - *Current educational literature calls for a shift in educational paradigm from a system of facts and tests to a system of curiosity, innovation and entrepreneurialism. Harvard psychologist Howard Gardner defines intelligence for students today as “the ability to solve problems that one encounters in real life, the ability to generate new problems to solve and the ability to make something or offer a service that is valued in one’s culture” [2]. Engineers in the field are models of learners for life. They have blended content knowledge, skills and competencies into an intuitive engineering sense. Engineers work collaboratively with others knowing that the best possible solution will be a negotiation between perspectives, boundaries and possibilities. They are flexible in their approach to new tasks, they learn from failures and they welcome uncertainty. Engineers are able to assess a situation, identify a component or process that could be improved, gather data, develop ideas, and create something, an item, process or service that is valued. What might education learn from engineering?*

Keywords: education, engineering, learning

1. INTRODUCTION

It is a critical time for schools. Will they carry on as educational institutions or will they emerge as centers for innovation, creativity and learning? More and more researchers and educational experts [5, 7, 8] are calling for great changes to the education systems. Today’s students will graduate into a world of incredible complexity and infinite possibility. Harvard psychologist Howard Gardner defines intelligence for students today as “the ability to solve problems that one encounters in real life, the ability to generate new problems to solve and the ability to make something or offer a service that is valued in one’s culture” [2]. Education professor and researcher Tony Wagner notes that “all successful innovators have mastered the ability to learn on their own in the moment and then apply that knowledge in new ways” [16].

Engineers in the field are models of learners for life. They have blended content knowledge, skills and competencies into an intuitive engineering sense. They collaborate to create new knowledge while welcoming multiple perspectives. They are flexible in their approach to new tasks, learning from failures and welcoming uncertainty. Engineers are able to assess a situation, identify a component or process that could be improved, gather data, develop ideas, and create something, an item, process or service that is valued. As stated by the National Academy of Engineering “No profession unleashes the spirit of innovation like engineering. From research to real-world applications, engineers constantly discover how to improve our lives by creating bold new solutions”. Engineers exhibit the very attitudes and competencies that educators seek to instill in their learners. What might education learn from engineering?

According to Koen [10] the work of an engineer is to employ “the strategy for causing the best change in a poorly understood or uncertain situation within available resources”. With this statement Koen reveals his engineering philosophy. Interpretation of each of the four main components; strategy, best change, poorly understood or uncertain and within available resources offers insight into the beliefs that shape the work of an engineer.

This philosophy of engineering and the process of learning are remarkably similar. Learning is seeking the best change for ourselves, the creation of new connections, new synapsis, and new competencies. When looking to learn something new, a learner is faced with uncertainty, their understanding of a situation is poor. Of particular interest to education is the strategies, these heuristics, which the engineer makes use of to build their solution, the development of intuition and comfort with ambiguity, as well as the ability to work creatively within restrictions. Drawing parallels between engineering and education allows us to rewrite Koen’s description of engineering as a statement of learning; the process of creating new understanding, competencies and actions from wonderings through rich and varied experiences and personal reflection.

A review of both engineering and education literature has revealed that engineers share several incredibly valuable characteristics of strong, independent learners. When combined these create a set of four guiding principles for educators. Each principle is rooted in engineering and adapted for the kindergarten to grade twelve education system. In the following section the principles are first situated in engineering, then presented as a vision for educators and finally developed as practical examples for engaging learners in our schools. Although described as four separate goals, the principles are strongest when implemented together.

2. GUIDING PRINCIPALS

Guiding Principle 1. Strategy

Education should cultivate in each learner an intuitive sense, a disposition to naturally draw upon a variety of flexible, non-standard, personal strategies in response to any problematic situation.

In the moment, engineers are called upon to make judgements and decisions that may result in the most unprecedented advancement for the betterment of humankind or in catastrophic failures. These in the moment decisions require confidence in oneself and the ability to synthesize prior experiences, evaluate innovative alternatives, reason through consequences and determine the most fitting choice at that time. To do so, one might suggest that engineers require a solid foundation of knowledge. We argue that this internal ability is much more than the recall facts and theorems. To Bucciarelli this engineering intuition means to “have some sense of the range of phenomena which might be so explained and how one constructs an explanation, develops ones open narrative and mathematical analyses when confronted with new phenomena, a new structural form, a new design. To know the meaning means to speak the language, to join the game, to know the rules and how and when they apply” [1].

It is knowing how elements work together, what pieces will fit, which pieces will not fit, what alternative solutions to try and when to regroup and start fresh.

Through experience engineers develop an intuitive sense of evaluating what information is available and what they will need to find out to determine their next step. Along with this intuition comes an awareness of calculation and theorems. Although aspects of the work today is completed by computer calculations Ferguson reminds us that we rely on engineers to check the reasonableness of their answers [6]. An engineer is then defined by “the set of heuristics he uses in his work, including the heuristics he has

learned in school, developed by experiences, and gleaned from the physical world around him” [10]. From this perspective, Koen concludes that “no two engineers are alike” [10].

In his retelling of the design process of the Wright brothers Bucciarelli includes the terms and phrases such as; figured out why, experimented, clearly knew, questioned, tried, reported, changed, compared, mistrusted, calculated, surprised, dug deeper where they had trusted before, concocted, designed, explored, manipulated, further compared, estimated, controlled for, explained their purpose, noted, reported, analyzed, deduced, re-shaped, re-thought and re-used, all of which highlight the flexibility of the process. Their responsive flexibility required persistence and a belief that failures were stepping stones [1].

Uncharted experimentation that begins with a thorough investigation of where we are now and a hypothesis of where we would like to be more closely describes the process than a labelled diagram with arrows and numbered steps to follow. For Ferguson a preset sequence of steps to follow implies a “division of design into discrete segments, each of which can be processed before one turns to the next” [6] rather than “the usual chaotic growth of a design” [6]. The open-endedness of an engineering design, the wealth of strategies, materials and processes that can be pursued allows for “many, many different paths, some of which are better than others but none of which is in all respects the one best way” [6]. Every situation is unique therefore every approach is an original.

In an engineer this intuition stirs a need to wonder, to question and to remain curious about the world around us. Engineers are looking for new problems to solve, opportunities to make improvements and reasons for innovation. At any moment, individuals should intuitively be able to assemble a number of possible approaches to problem solving and design, evaluate the potential of each method, select a response best suited to the situation at hand and engage in action with confidence. It is only when the lived personal experience and the theoretical content are tied together that a true understanding of the world begins to take shape.

Strategy in education. As an engineer develops a strategy for designing solutions and inventions a student must develop a strategy for learning. This unique, individually defined schema is echoed by Kolb stating that “the learning process is not identical for all human beings. Rather, it appears that the physiological structures that govern learning allow for the emergence of unique adaptive processes” [11]. A student approach to learning should be personally defined over time through experiences in a variety of

learning environments. These environments must not be limited to our four walled classrooms. They should extend in all directions to include places such as the zoo, the hardware store, the art gallery, the hockey rink and the grocery store. The students should come to recognize which strategies are best suited to themselves as a learner and best suited to the task at hand. Just as Koen [10] noted the uniqueness of each engineer the same is true for learners, no two are the same.

When given an opportunity to define their own questions students develop a wide variety of personal learning strategies. When a student finds themselves in the middle of an ill-defined, problematic situation they will need to select an appropriate next step from their kit of strategies. An ill-defined or ill-structured problem refers to realistic, complex, authentic problems that are messy to work with and not limited to a right or wrong answer. Students would need to analyze their current level of understanding, assess what information they require and implement a strategy to support the discovery of that information.

We propose that students and teachers build their own learning paths by combining strategies such as exploring, researching, developing a plan, creating and constructing a possible solution, drawing connections to other subject areas and to prior knowledge and experiences, reasoning, communicating with symbols, visuals and words with authentic audiences beyond their classrooms, and reflecting. This focus on the process of learning is meant to establish the belief in all of us that the goal of education is to learn how to keep on learning.

Creating opportunities for students to explore problematic situations is key for the development of intuition. By orchestrating experiences where students “experiment, take risks, and play with their own ideas, we give them permission to trust themselves” [12]. The classroom community should be a place where students can try a hunch, experiment with possibilities and reaffirm ideas. Educators are encouraged to invite students to ask their own questions through inquiry projects and problem-based learning. Creating spaces for experimentation and design is also valuable. Educators should also look for opportunities for students to reflect on their learning through portfolios and learning stories.

Guiding Principle 2. Best Change

Education should unleash in each learner a passion to create positive change in the world through innovation and invention as a result of working collaboratively with others in creativity-intense environments.

The work of an engineer is to make the world a better place. Through design, engineers envision structures, places, machines, systems and processes that will be valued in society. Engineers are responsible for great inventions and innovations as well as the best fit solution in an emergency. To meet these demands engineers work collaboratively with a variety of experts immersed in “an atmosphere of optimistic enthusiasm” [6].

Engineers specialize in a variety of fields. Each brings with them a set of experiences and strengths that shapes their view and frames their thinking. As different as they are, the process of engineering is common to them. A best solution will require that engineers carefully consider the variables influencing the situation and the possible impacts of their decisions.

In collaboration, each individual adds to the collective picture by sharing their own views. Each view is defined by the beliefs and experiences of the individual. Because we have not shared the same experiences each of us sees in our own way, through our own lens. On the surface these differences may appear to be a deficit, inhibiting cooperation and understanding among teammates. However, when viewed as wealth, this multitude of perspectives offers the best picture of reality. To arrive at the best possible outcome we expect a give and take, a negotiation of the best each perspective has to offer.

Each of us has much to offer. Our own views and expertise added to a design creates a more fluid and inclusive definition of knowledge. This definition seems much more relevant as we are constantly adding to what we know. To say that “knowledge becomes, not a packaged commodity, but an event” [14] is to adopt a growth mindset, a genuine learners perspective.

Best change in education. Problems and topics that students examine in our schools should be original, meaningful and authentic. Solving problems that only the teacher poses, for which the one right answer is already known, does little to stimulate an interest in contributing to the betterment of our world. At this time there are many problems in our world that students could investigate as part of their required curriculum. In their *Transforming our World: The 2030 Agenda for Sustainable Development*, the United Nations suggests engaging students in questions relating to eliminating poverty, ending hunger and food insecurity worldwide, creating and implementing a global health care standard, managing sustainable waste systems, increasing access to reliable, clean energy for all, creating opportunities for meaningful, productive employment for all, eliminating inequality, designing safe and sustainable cities, and conserving

oceans, forests and global biodiversity [9]. Local questions such as developing a community garden for a food bank or designing an accessible entrance to a second floor classroom, are equally valuable. Each of these questions opens an infinite numbers of responses. Students will need to learn to evaluate the implications of their plans, drawing on evidence in favor of and against their ideas. Any solution will be a negotiated give and take between parties. Ultimately a solution for today will represent one possibility that to the best of our knowledge and within the given limitations of time, budget, resources, expertise. Our best answer today will set the stage for further research and development in this area so that a solution created by a student tomorrow will be even stronger.

Each learner is unique in their experiences and views the world from their own perspective. Collaborating with teammates whose experiences are different and who have expertise in other areas to share is essential for success in the 21st century. Individuals are empowered when personal intelligence is pooled and steered towards a common goal.

The need to develop skills in communication and collaboration is at an all-time high. In 21st Century Skills, Dede notes that “the degree of importance for collaborative capacity is growing now that work in knowledge-based economies is increasingly accomplished by teams with complementary expertise and roles” [3] rather than by an individual working on their own. In educational settings communication is developed through collaborative learning groups, discussion, writing and reading in all content areas, producing videos, managing websites and learning blogs as well as through the arts. For the 21st century learner communication is not limited to the spaces and people within their classroom walls. Authentic audiences provide a purpose, a vision for who their work is important. With technology students may find themselves collaborating with peers from all over the world.

To be creative is to produce or grow new ideas, items or actions by combining thinking in new ways. A creativity intense culture is rich with optimism, imagination and enthusiasm. Such a place enables the development of the novel ideas through experimentation. This environment would support the sparks of creativity that first imagined a refrigerator, a solar panel, a space craft and an iPod. These supportive cultures embrace mistakes and failures as opportunities for better understanding. Innovation comes from combining and recombining ideas, components and pieces.

Wagner recommends organizing the learning culture of a school around “thoughtful risk-taking, trial and error, creating, intrinsic motivation: play, passion, and purpose” [16]. With a goal of creating rather than

consuming knowledge our schools must offer rich learning environments that promote a constructivist approach to teaching. They encouraged first hand activities such as exploring, building, taking apart and designing. The role of the educator in these environments is to prepare situations where questions would develop from the experiences being had and would, for each learner, meet them at the edge of their current state of understanding pushing them to build new ideas.

Schools as creativity-intense environments for both teachers and students will stir the development of fresh thinking, original ideas and positive change. Creativity, as a current, should flow beyond the arts and into all subject areas.

Principle 3. Poorly Understood or uncertain

Education should develop in each learner the confidence to let curiosity take over, to explore, to pose authentic questions, to investigate additional factors that will influence the solution, to turn ambiguity into determination and failure into invention.

Koen captures the poorly understood and uncertain nature of engineering in writing that “engineering has no hint of the absolute, the deterministic, the guaranteed, the true. Instead it fairly reeks of the uncertain, the provisional and the doubtful” [10]. Each problem encountered by an engineer has its own set of context dependent characteristics and outside factors. Each of these elements can impact the process and solution in any number of ways. They may derail the perfect plan with additional industry requirements, reroute a process as a result of time or entirely roadblock a project due to budget restraints. The engineering process is creative, inventive and fluid so that the engineer can respond to the unexpected.

Confidence and comfort with not knowing is cultivated through experiences where uncertainty exists. Both successful and unsuccessful experiences deepen our understanding. Failures, small scale and catastrophic, are instructive. For learning to come from a failure engineers engage in an in-depth study of what was involved. Each component, material, process, and function is examined.

Poorly understood and uncertain in education.

Much of a child’s day at school is predictable. The routine of classes and schedules provide a structured, similar pattern to every day. Traditional classroom roles of the teacher as keeper of knowledge and student as obedient recipient of information are well defined and understood by even the youngest children before beginning school. Often course materials are predetermined as lessons plans, texts, assignments and

evaluations are similar from year to year, class to class. Problem sets given by the teacher do not afford students a wonderfully complex question to analyze. Most often these repetitive assignments ask that students repeat a process illustrated by the teacher to arrive at the same answers as their classmates. The single right answer to these assignments has already been printed in the back of the book. Schools have succeeded at creating a very consistent, reliable model. However, they are also succeeded in creating students who are compliant memorizers. Why teach students to solve problems for which we already know the answer? Learning is most likely when students are met at the edge with a challenge that will allow them discover something new, something foreign, something exciting.

Fieldwork offers students the chance to take on the role of engineer outside of the classroom, in the very environment where engineers do their learning and work. While on site students are active investigators, applying the research tools, techniques of inquiry and standards of presentation used by professional in the field. Being in the field pushes both the teacher and the learner to try new things that they may not have had the opportunity to try elsewhere. Roberts insists that “children must actively sense and feel their immediate surroundings and it is the educator’s job to provide the freedom necessary for the child to follow his or her natural inclinations” [15] exploring these spaces.

Fieldwork is inspiring for the learner as it places them directly in the problem, no longer outsiders reading about a problem or spectators watching. They are the main characters. Students interact with and respond to the elements of the situation. Reacting in the field is consistent with view of knowing as knowing to respond and act in the moment, when the information is immediately required.

Field work is intended to be risky and rewarding. This risk provides the uncertainty that cannot be matched in the classroom. Just as professionals dealing with unknowns develop an intuitive sense, fieldwork develops comfort and with ambiguity in young learners. This risk-taking generates confidence. The lived experience in the field lets students construct for themselves a more complete understanding of the world around them

The ability to navigate ambiguity and uncertainty requires a balance of content knowledge and the capacity to develop creative and innovative ideas. As students learn to construct their own problem strategies they will inevitably encounter difficulties. These difficulties, misunderstandings, misconceptions and errors, generate an even greater platform for learning. By confronting difficulty students must examine their process, justifying and verifying each decision. This revision can offer valuable insight into

thinking and should be encouraged. Once a student has worked through a difficulty or an impasse this new understanding is used to further support their reasoning towards a more viable solution.

When we invite uncertainty we invite failure. Applying Petroski’s statement that “scientific understanding didn’t progress by looking for truth; it did so by looking for mistakes” [14] to education he suggests that failures, and their examination, should play a prominent role in developing learning behaviors. Productive failure first sees students wrestle with challenging problems for which they do not yet have the skill level to complete. They will reach an end point in their path, at which point scaffolding, facilitation and instruction are introduced to guide them further. Through this combination learners benefit from self-directed problem solving and instruction as needed to clarify any misconceptions. The questions students tackle should be just beyond their current ability level so that they find themselves in just over their heads yet not too deep that they cannot see the possibilities.

Principle 4. Available Resources

Education should inspire in each learner a belief that where there are limits, there are possibilities. Let’s use all spaces as learning places.

When faced with a problem to solve or a design challenge an engineer must evaluate a multitude of factors. Consideration is given to scientific principles, mathematical calculations, political interests, social and economic constraints, ethic issues, manufacturing, environmental sustainability and aesthetics. Along with these visible parameters are available personal resources. Each member of a design team, as well as the consultants and external collaborators, brings a strength to share. Expertise in a subject area, technical understanding, and past experiences are considered available resources as well. For the engineer, knowing their strengths is key. Of equal importance is knowing one’s limitations. Being able to identify an unknown and together devising a path towards knowing further strengthens each team member.

Available resources in education. In a traditional education model students are given tasks for which all the necessary information is known to them. There are no variables to define, no measurements to gather, no decisions to be made. Students are therefore denied the opportunity to develop the analytic thinking skills needed to generate a list of limitations and possibilities as well as the critical thinking skills required to scrutinize each factor on that list to assess its potential impact. These types of problems create the conditions for students to believe that every problem has a

readymade solution, that following the step by step procedure laid out by the teacher is what learning is all about and that if you can arrive at that one correct answer quickly, you must be really smart. Unfortunately, this line of thinking does not serve students well.

A wealth of available resources can be found in the communities beyond the doors of our schools. Places, spaces, people and activity can serve as learning resources. To access these resources students need to explore their communities. When learning reaches from the classroom into neighborhoods is build a connection between theory and practice, between concept and process, between content and context. A learning expedition requires that students become part of an uncertain, curious, problematic situation, surrounded by the factors that will define the limitations of a solution.

In order to develop the ability to define the constraints acting upon a problem and mesh those with possibilities student need practice in the field. Roberts highlights the importance of living the learning when he notes that “thinking cannot be removed from the world in which we live” [15] and these problem solving and critical thinking skills “are generated from experimentation in unique times and places” [15]. Education lived solely in the fabricated contexts of a well-managed classroom will not suffice.

In *Experience and Education* Dewey [4] recommends a system of education based on lived experiences. For convenience and control, we have taken the term experience to mean the experience of copying off the board and filling in the blanks while seated quietly at a desk with a pencil. This style of education offers students the opportunity to develop a very narrow set of skills favoring theoretical knowledge and conformity. These lessons often make use of “fake world” [13] problems, problems that claim to have connection to the real world but fall short, that are well defined, compartmentalized, and predictable.

Educators looking to develop authentic problem solving situations with their students may try expeditionary learning, which engages learners in authentic, non-routine inquiries through direct encounters with the content being studied. Here students take on the role of scientific, environmental researcher, designer, architect, mathematician, historian, geographer, and engineer in the very environments where these professionals do their learning and work. Learners become the main characters in these problems interacting with resources, places and people. An expeditionary learning experience seeks to inspire a spirit of wonder and curiosity about learning that stays with each learner for life. Let us challenge our view of schools to

one that is boundary free. By extending our learning in all direction we welcome all learners with accessible content, a range of actions and endless possible paths.

The divisions of school subjects further limit learning. A multidisciplinary approach, where the focus is on learning and content is achieved through contexts, further extends the possibilities of school. In our world, the city and the wild spaces, are not differentiated into disciplines. When the ways of thinking, synthesizing, and creating that are present in all subject areas are lived together a true multidisciplinary approach emerges.

3. CONCLUSION

The guiding principles suggested in this paper resonate with a constructivist philosophy of education. Educators who adopt these guiding principles will help learners to fully benefit from engineering philosophy. Experiences working with problematic situations will support the development of an intuitive sense in each learner. Opportunities to conduct original research, create and design will develop a variety of flexible, non-standard, personal strategies that learners can call upon throughout life. Teaching and modeling learning behaviours that allow learners to approach problems from their starting point, carve their own paths and present multiple solutions will develop in students a flexible response to problems and the seamless inclusion of all learners. For educators, cultivating in each learner an intuitive sense, a disposition to naturally draw upon a variety of flexible, non-standard, personal strategies in response to any problematic situation is best accomplished by offering learners opportunities to define their own questions, by encouraging an open approach to solving problems rather than a prescriptive one, by welcoming novel ideas and invented strategies and supporting learners in developing their own paths.

Purposeful authentic problems create space for real thinking, negotiation and reasoning. A commitment to working towards positive change in the world through innovation and invention is realized when students have opportunities to ask their own questions. Teamwork and collaborative skills are best developed through interaction with others, supporting peers and through a responsibility to the shared learning of the group. The solutions to today’s problems will require a rich imagination as such schools must become creativity hubs where the buzz of innovation calls to all learners. Unleashing in each learner a passion to create positive change in the world through innovation and invention as a result of working collaboratively with others is best achieved by tackling questions for which the answer is not yet known, but for which any development of ideas will contribute to a cause greater

than ourselves. By inviting individuals to share in the learning adventure together we build the scaffolding and competencies students will need to be contributing teammates, leaning partners and valued citizens. Establishing schools as creativity-intense spaces lets brilliant designs take shape.

Developing in each learner the confidence to explore what is unknown and to pose authentic questions, to investigate additional factors that will influence the solution, to turn ambiguity into determination and failure into invention is realized though new experiences and adventures where learners are met with challenges far greater than they have seen before. As in engineering, the starting point for learning is a poorly understood or uncertain situation. To be fully prepared for any situation is unlikely but the ability to see possibility in uncertainty is a valued characteristic. Curiosity will remain a key component of success for years to come. Learners must know that we value their contributions and that we are willing to follow their lead. Uncertainty uncovers potential for courageous actions and perseverance atypical of our rectangular classrooms.

Inspiring in each learner a belief that where there are limits, there are possibilities is built first by analyzing the context of each problem, its core and periphery, so as to determine its boundaries. Then examining these boundaries we see where we can go further, what new ideas can push forward and which new skills will need to be developed. As engineers continue to demonstrate, the ability to go on learning is the most valuable resource available to us.

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