AC 2011-1775: ENGINEERING IN A MONTESSORI ENVIRONMENT

Catherine Frances Ibes, St Catherine University

Catherine Ibes is Assistant Professor in Montessori Education at St. Catherine University in St. Paul, Minnesota. She has co-developed and co-taught three STEM courses in a Montessori STEM Graduate Certificate on the topics of Earth/Space Science, Engineering, and Mathematics and Science. In addition she works as full-time faculty member in the Montessori education department. Previous to her University position, she worked for 7 years in elementary schools.

Yvonne Ng, St. Catherine University

Yvonne Ng, M.S.M.E, teaches computer science and engineering at St. Catherine University. Educated at Princeton University and the University of Minnesota as a mechanical and aerospace engineer, she worked in industry as an automation design engineer and contract programmer. She made computer science a more appealing topic for her all-women undergraduate student body by presenting this technically valuable course in a project-oriented comprehensive manner. She is currently the director of the Center of Excellence for Women, Science and Technology where she administers the college's National Science Foundation scholarships for Science, Technology, Engineering and Mathematics (STEM) majors and facilitates various recruiting, advising and placement activities for STEM majors and minors.

Engineering in a Montessori Environment

The first female doctor in Italy, Dr. Maria Montessori, first developed Montessori education over 100 years ago. Practiced in over 200 public schools in the United States and Canada, and in thousands of schools worldwide, Montessori education is known for fostering self-discipline and creativity hand-in-hand with independence and social responsibility. Successful graduates of the system include Google founders Larry Page and Sergey Brin, the founder of Amazon, Jeff Bezos, Nobel laureate Gabriel Garcia Marquez, and Anne Frank.

St. Catherine University's Montessori STEM (MSTEM) Graduate Certificate, a 3course certificate program, was developed for in-service Montessori educators to offer enrichment of existing Montessori content in Science, Technology, Engineering and Mathematics (STEM) subjects. All the courses were codeveloped and co-taught by a science or engineering content area expert and a Montessori pedagogical expert. The engineering course in particular greatly impacted existing Montessori curricular content by deepening connections across disciplines, informing Montessori pedagogy, and addressing the requirements for new engineering content in Minnesota state standards. While engineering presented a new and very effective method of problem-solving to teachers and students alike, it also provided a crucial link between two foundational Montessori concepts: the fundamental needs of all humans and the evolution of human ingenuity. Engineering proved to be a perfect fit in the Montessori system of education.

Montessori education also proved to be an excellent fit with engineering education at the elementary levels. Montessori education is holistic in nature and uses developmentally appropriate, hand-on, didactic materials to inspire engagement and learning in children. Inquiry is fostered through initial experiences (lessons) that offer both inspiration and instruction, and through the follow-up work (assignments) that encourage children to deepen their understanding through continued exploration and application of the materials and concepts. Design is an essential element of the Montessori environment.

A key message in Montessori education is gratitude for those who came before, linking students' modern lifestyles back to the many nameless engineers who came before. Additionally, Montessori education inspires students to think about the gifts that they have to offer to the future generations. Our work with engineering today in the classroom is sure to bear fruit in cultivating the engineers of tomorrow.

Through the lens of Montessori pedagogy and curriculum, engineering comes alive in the study and exploration of human needs. At the same time engineering affords a practical and process-oriented approach to developing systems for Montessori classrooms and curriculum. This paper outlines and explores the Montessori method of creating meaningful context and highlights the ways in which the engineering design process deepens the Montessori instructional approach, illustrating how the collaboration between Montessori pedagogy and engineering experiences will inspire and prepare our next generation of engineers.

1 Integrating Engineering into a Montessori Curriculum

In 2008 Medtronic funded a three year study of STEM (Science, Technology, Engineering and Mathematics) coursework for Montessori elementary educators at St. Catherine University. The goal was to create courses on three distinct topics within the STEM matrix: Science, Engineering and Mathematics (with Technology integrated into each course). These courses were developed to increase teacher content knowledge and confidence in STEM areas and to improve student understanding of STEM content.

1.1 Montessori STEM Graduate Certificate Program

Together, these three courses formed the Montessori STEM (MSTEM) Graduate Certificate following fundamental Montessori principles. The STEM content and experiences were developed to grow naturally out of the existing Montessori elementary curriculum, allowing for their relatively seamless integration. It was believed that this approach would make implementation more natural and exciting—the content built upon and extended core Montessori curricula, as well as offering hands-on engaging activities to enrich existing lessons.

The second course in this Graduate Certificate was on the topic of engineering. The timing of this was especially good as engineering became part of the state of Minnesota Science standards in Fall 2010, making it the second state to include engineering in its educational requirements. The Montessori program saw this course putting them on the cutting edge of education worldwide. Eleven teachers, ranging from early childhood to 6th grade, were part of the first cohort of the MSTEM Graduate Certificate program.

1.2 Developing a Professional Development Framework for Elementary-level Engineering

Because the lessons were meant to engage on multiple levels, teachers in the STEM Graduate Certificate Program experienced the lessons, using kit materials in much the same way the children would, later, in the classroom. Teachers were introduced to a concept and then the lesson that explored the concept. They did the activities in small groups with support from the Montessori and engineering instructors as needed. Following the Montessori model, the lessons connected the concept to experience, which facilitated the development of deeper understanding, and in many cases, deeper questioning. The group then reconvened to discuss any questions that emerged during the activity with regards to the activity and/or the underlying concepts it demonstrated.

Evaluation at this time revolves around teacher competence, confidence and comfort with bringing engineering into the classroom. Fuller evaluation of student learning will follow later as the children complete the three year cycle of instruction.

1.3 Transferability of Lessons Learned

This paper covers insights made while integrating engineering into a Montessori curriculum, especially on how the foundations of engineering design can be taught in age appropriate ways to all students.

Although not all students have the opportunity to learn in a Montessori setting, the principles of instructional design are transferrable to other educational settings. Moreover, the Montessori methods derive from Maria Montessori's success in teaching all children.

Montessori practices emerged early in the 20th century, when the first female doctor in Italy, Dr. Maria Montessori, observed that didactic materials used with 'deficient' or mentally disabled students resulted in improvements in test scores to such a level that in some cases these students performed as well as 'normal' students. In time she began working with young children in the slums of Rome who were untended during the days while their siblings were at school and their parents were working. These children, ages 3-6, were placed in a room and various didactic materials were made available for their use. Over the years that Dr. Montessori observed these children, she evolved and modified a design for the physical classroom, curriculum and a methodology of education that eventually bore her name. In time her work became extremely well-known, with dignitaries visiting the rustic classroom, and a 'glass classroom'—complete with materials and children working—was showcased at the World Fair of 1919.¹

1.3.1 What Engineering Does for the Montessori Curriculum

Engineering offers Montessori teachers a way to access many of the deeper concepts embedded in a lesson. In each case where engineering was added to a lesson or unit, it sprang to life, allowing for more critical engagement and inquiry as well as the influx of new content—and activities to explore that content. Engineering made Montessori even more hands-on, more interactive, more dynamic and engaging to students. Work with the design process allowed for a more interdisciplinary approach—any number of connections could be made between engineering and science, mathematics, technology, history, and geography. Engineering became a connective thread that brought these content areas together.

Engineering, and in particular the Engineering Design Process, provided an opportunity for further professional development to these educators. The Montessori environment and class systems are holistic: they address the academic education of the child while also developing their social, emotional and personal growth. This is no small task, and means that the designed systems of the class systems and environment must provide both structure and independence (the 'need').

A foundational premise in Montessori education 'freedom within limits.' Dr. Montessori believed these were two sides of the same coin: the structures that limit the child

(discipline) are also the structures that leave space for freedom and inner discipline to emerge and develop.

However, the freedom offered the children in this setting must be predicated on very clear and well thought out systems of engagement and interaction or chaos emerges and entropy ensues. These systems require a great deal of advanced (and ongoing) preparation on the part of the teacher—a design process—long before the children enter the room. The design includes the ordering of the physical environment (called the 'prepared environment), the social structures (called 'grace and courtesy' lessons), classroom systems (record keeping that fosters the children's independence and accountability) as well as, of course, the curriculum. Montessori educators greatly benefitted from the process that engineering brought to these preparations.

By the end of the course, teachers in the certificate program felt like problem solvers, and hence like engineers. The concept of engineering was no longer foreign or frightening. Instead, it was an enterprise that inspired them to roll up their sleeves and engage.

1.3.2 What Montessori Does for Engineering

Montessori methods underscore the importance of three main elements that current engineering education usually includes, but may not have articulated as clearly as the Montessori system:

- 1. **The Power of the Story to Engage.** Many publications in engineering education literature discuss the need for a meaningful context.² In some ways, engineers may take this for granted as engineering focuses on solving problems to meet needs.³ In the Montessori system, this context for the human need is explicitly required and practiced.
- 2. The Role of the Sensorial While Teaching. Hands-on activities have been touted as essential in early engineering education. As engineers, experience with tools and technology as well as creating real solutions to problems are essential, but the relationship of these "skills" with the larger abstract concepts and higher order thinking are not as well documented. In fact, there is still debate about whether engineering can truly be taught at lower grade levels.^{4,5} The Montessori system, however, has very explicit roles of sensorial experience in its curriculum, treating these as essential foundations for leaping students into abstract concepts. This Montessori approach to the development of curriculum requires moving from whole to parts, concrete to abstract, known to unknown. In studying birds, for example, the Montessori educator begins a lesson series by bringing in a live chicken, which represents the 'whole' (a living bird), the 'concrete' experience, and the 'known' concept to the children. This lesson can then be followed up by studying the parts of the chicken (feathers, beak, etc.). The parts can be presented using some card material (more abstract) and moving from the child's known experience (what is a chicken?) to the unknown (what are the parts of the chicken?). These concepts were used when creating the lessons and activities in the course, infusing the engineering curriculum with a Montessori approach.

3. The Learning Spiral in Evaluation. Evaluating a creative process like engineering design can seem tricky to those educators used to having quantitative measures such as test scores on discrete facts and skills.⁵ The Montessori system is built on a three-year clustering of children where they are exposed to the similar concepts multiple times, each time with greater depth and complexity. This spiraling facilitates the gradual building of knowledge over time, rather than a unit of experience that is quickly learned and then just as quickly forgotten. This patterned re-exposure and exploration is integral to Montessori's approach, and is the larger framework from which teaching from the whole to the parts, from the concrete to the abstract, and from the known to the unknown are designed and set in motion.

Section 2 briefly discusses the process used by the Montessori and Engineering experts on how to integrate engineering into the curriculum. Sections 3-5 provide more details on how each of these elements were used while integrating engineering into the Montessori curriculum. They include preliminary results from teacher competence, confidence and comfort with the material as they include engineering in their classroom. Section 6 draws some conclusions and discusses the next steps in the elementary engineering professional development process.

2 The Development Process

To prepare for the summer course the Montessori expert and content area expert spent a year previous to the course in collaborative dialogues and writing. The phases of this process included:

- 1. Learning about each other: As a first step, the Montessori expert gave the engineering expert readings while the engineering expert had the Montessori expert go through introduction to engineering exercises. This gave the other some foundational understanding and a basis to ask more in-depth questions. This was an important first step to finding common ground. The Montessori expert saw that systematic problem solving was an essential part of engineering that had great promise within the Montessori program while the engineering expert saw the balance of sensorial experience and spiral learning was fruitful for teaching engineering foundations.
- 2. **Curriculum-specific brainstorming:** In the next phase, the Montessori expert took the engineering expert through a typical set of lessons. Through this, two Montessori content areas were identified as the richest potential for the seamless integration of engineering: the Great Lessons and the Fundamental Needs of Humans. The engineering expert experienced the lessons as given by the Montessori expert but explained how she saw the lessons through her 'engineering eyes.' It was decided that the engineering design process would be a core theme across the curriculum. It emerged as a framework to refine teaching methods and pedagogy, classroom systems, curriculum and understanding of engineering through the range of children's ages.
- 3. **Identifying key engineering concepts:** The engineering expert then took the Montessori expert through key engineering activities and they discussed the main concepts children

would learn. In particular, they determined the 3 levels of understanding required for the lessons for each three-year age grouping. This helped the engineering expert scaffold the learning expected with each subsequent exposure to the activities. The Montessori emphasis on sensorial experience pushed the engineering expert to evaluate typical engineering activities and articulate the main concepts intended by each.

4. **Designing the lesson:** The Montessori expert then took the lead in working with the engineering expert to design lessons that fit within the Montessori pedagogy. Together, they leveraged Montessori's knowledge of what captures children at each age level, prepared lessons that moved from whole to parts, concrete to abstract, and known to unknown, determined follow up and extension activities that would lead to the next level of engineering in the spiral, and framed the activities in ways that would excite the children as they were re-exposed to the lesson in the future. The engineering expert constantly checked back to the ABET and Professional Engineering systems to verify the importance of the different concepts while consulting with the Montessori expert about what was appropriate to expect from children at each age.

The instructors believed that if Montessori teachers saw engineering an enhancement to what they already knew, they would feel more confident in their own abilities to learn about engineering and feel more comfortable with integrating it into their classrooms. They would see engineering as an essential part of their lessons rather than an add-on.

3 The Power of Story to Engage: Technological Development

The Montessori curriculum is founded on five 'Great Lessons,' large overarching lessons that begin each year for the elementary child. These 'story lessons' are largely historical and scientific in nature.

The first story, "The Story of the Universe," tells the history of the origin of the Universe 13 billion years ago and ends with the formation of the Earth, about 4.6 billion years ago. The second story, called "The Coming of Life," picks up at the early origins of the Earth and outlines the emergence and evolution of life on our planet. The third lesson, called "The Coming of Humans," chronicles the evolution of humans, from Homo *habilis* to Homo *sapiens*. The final Great Lessons deal with two further developments of human culture: mathematics and written language. Together these five lessons serve as a large organizing structure to which the children return each year, allowing them to synthesize information from the previous year by seeing and hearing it, again, embedded in a larger context.

We focused our new engineering lessons on The Coming of Humans which offered unique opportunities for the exploration of engineering concepts.

3.1 The Existing Montessori Framework

The Coming of Humans, the third Great Lesson, begins about 2 million years ago with the first species in the Homo genus: Homo *habilis*. The lessons that lead from this 'Great Lesson' are

organized by a physical Timeline of Early Humans, an illustrated roll of paper 10 feet long by 2 feet wide, that traces the broad strokes of human evolution through a series of vignettes (scenes) from the lives of early humans to the modern day. Parallel to these vignettes are images of the tools that marked this evolution. The story of the Coming of Humans is an overview lesson that is followed by an in depth study of the five major species of the *Homo* genus: *habilis, erectus, heidelbergensis, neanderthal* and *sapiens*.

3.2 The Engineering Connection

One of the first vignettes on the Timeline accounts for a crucial difference between humans and other animals and sets us on our path of engineering: Homo habilis ('handy man') is shaping a tool. As the first evidence of intentionally modifying the environment to meet a need, it may be the beginning of engineering in human evolution. Presenting engineering within this context makes it associated with a natural human enterprise, not something for only the special few.

We used the power of the narrative to draw teachers and children into the story of engineering. These unfold from this Great Lesson to show how each development was exciting and dynamic. *Habilines*, one of our earliest human ancestors, are significant in the history of evolution because they took something out of their natural environment—a stone—and consciously and intentionally *altered* it to meet their needs. In the realm of adaptations, this is surely one of the most valuable: humans' ability to adapt/alter/design their environment to satisfy their needs. While previous hominid ancestors certainly used tools (as do many primates, birds and other animals today), the distinguishing characteristic of this 'handy human' is the presence of *shaped* (designed) tools.

3.3 Tool Development: Using the Great Lesson Stories to Introduce Engineering

The story telling mode of the Great Lessons is used, and the associated timeline is used along with objects and picture cards, representing the evolution of tool development. The story starts with Homo genus who added to their diet of roots, tubers, berries and termites by sharpening rocks (object or card laid on timeline) so they could break open bones, accessing the protein rich bone marrow within. With this rich protein source they could 'afford' a larger brain. They learned to harvest and then harness fire, creating the earliest hearths, providing their small communities with warmth, light, protection, and, eventually, improved nutrition through cooking.

Improvements in diet allowed for the emergence of even larger brains, which in turn enabled more engineering skills to emerge. In time this spurred the development of a sharpened stick (object or card) for hunting and the improvement of the design by fire hardening of the tip (object or card). Now humans were not limited to close range with a hand held stone. With this new engineered technology, they could hunt animals from an arm's length.

Diet improved. Larger brains, as they emerged, could be supported by their new meat enriched diet. In time the spear was developed, with the innovation of a removable arrowhead (object or card). Over time humans became more accurate and could hunt at increasing distances with the

atlatl, or spear thrower (object or card). Eventually, around 25,000 years ago, the bow and arrow (object or card) revolutionized hunting.

Transferable Educational Element: By addressing each technological advantage as a mindful development by humans, engineering, not a force of nature, becomes its own story in human development. The narrative underscores the accomplishment of humans to extract from and use the environment in a way that perhaps no other species can match.⁶ In this lesson, engineering is represented as humanity's ultimate tool. As children study human evolution, they continue to discern (unpack) the separate events that contribute to the advancement in hunting technology. When other technologies follow, engineering becomes the framework children use looking at tools.

3.4 Wheel Development: Using Fundamental Needs to Introduce Larger Context of Engineering

As children in Montessori elementary classrooms learn and study, similarities and differences between cultures are pointed out from the vantage point of 'Fundamental Needs.' The concept is a natural extension of the narrative story, bringing the children's understanding of the story to the larger scope of the real world in which they live. The result is simple and profound: children realize that all humans have the same basic needs. The fulfillment of these needs is required for survival. The great diversity of human culture is expressed through the variety of ways in which different people, living in different regions, telling their own unique cultural stories, fulfill these needs.

Montessori identified two main categories of Fundamental Needs: physical and spiritual. The physical needs consist of food, shelter, clothing, transportation, and defense. The spiritual needs consist of art (all disciplines), communication, love and a belief system. While these lists are not intended to be fully exhaustive, they are an organizing structure around which learning and discovery can occur to show children how different communities fulfill the same needs.

For example, using the Fundamental Needs charts, children study people of the 7 continents (Antarctica included, though no native population is present). Children may look at Asia, for example, and see images representing how a community on that continent meets all of their physical and spiritual needs. In a later study, children may compare the different solutions cultures have created for meeting the same need. In studying shelter, for example, a child might see the yurt of Mongolia, the cob house of England, the teepee of the Native American, and so on. The Fundamental Needs is at once a peaceful acknowledgement of the commonality of human needs as well as a celebration of the diversity of 'designs' that make each of these rich and varied heritages unique.

These Fundamental Needs lead into the history lessons in Montessori upper elementary. We used Fundamental Needs of transportation to introduce engineering yet again, but at a higher level. The fifth grade study of the history of human culture was an excellent time to explore the evolution of design. A large timeline exists that follows human 40,000 years of human culture, beginning during the Upper Paleolithic. For the study of transportation we chose the wheel because of its significant impact on civilization.

Eight images of wheels through time were selected to show the innovations of wheel design throughout its nearly five thousand year history. These designed solutions included the use of wooden spokes, copper rails, a change in position beneath the chariot, wire wheels and eventually the pneumatic tire. In the lesson, each design improvement was analyzed and traced to a civilization and time, as well as to the ways in which the wheel was utilized in that culture.

Transferable Educational Element: Through the addition of engineering, the study of Fundamental Needs became deeply interdisciplinary. A study of engineered designs illustrated engineering's role in history while providing a framework for students to analyze the solutions each culture devised. Since there is not one perfect design in engineering, children learned that every design has its own assets and liabilities. This opened the door for discussion amongst the children and invited critical inquiry.

3.5 Findings From Using Montessori Elements of Narrative and Fundamental Need

- Narrative Underlined the Context and Gave It Value: Using the study of human evolution underscores the innateness of our designing abilities: all humans engineer. Just as language is explored in Montessori through discovery, unpacking what we already do naturally, this activity shows how engineering flows from the central premise that everyone, everywhere, engineers already. Some post-course comments included:
 - "I see engineering and opportunities for teaching/talking about it all around us. I can apply the terms and explain it in 'teachable moments.'"
 - "[I have a] new passion for what engineering is. It has terrified me since I was in high school and I thought engineering was an unattainable career. Now knowing what engineering is, I may have pursued it – I love problem solving and finding the most efficient way to do something. If I had known that maybe I would have pursued it."
 - "I went from knowing the word engineering and feeling that it was too difficult, that it's for really smart people, a far away concept I could never reach... to talking about it and pointing out what engineering is and I see it everywhere in the classroom. You can't grow further than that."
- The Effort to Integrate Engineering Rather Than Add-On Was Appropriate: Teachers in our MSTEM Program were inspired to re-envision their work and methods in the context of designing and engineering. Engineering suddenly became attainable to them. Post-course comments included:
 - "Engineering to me was something that was un-teachable. I have found that we already teach it. My students were very receptive and eager to learn more about engineering concepts."
- Human Needs Gave Children Purpose to Their Work: Connecting engineering to history and human needs made it accessible for many more students. The context, the stories, the experiments and discovery struck their imagination and made them, and their

elementary aged students, feel confident and engaged in this work. Teacher observations included:

- "The children loved all the movement and experiments (hands on) that we did. They really enjoyed the 'problem solving' component to the materials. It was very engaging!
- "[Engineering lessons] captured students you hadn't captured before. I saw girls take off and feel confident. Girls loved design process and this was helping build confidence in kids and a love of learning that spark. Kids think they are scientists now. They say, 'I'm going to be a scientist when I grow up!' It's so active and involved especially engineering and it builds confidence and attachment to the concepts."
- "All in all, the children love the engineering lessons and ask for more. They want to be engineers when they grow up. Their parents were impressed with the children's engineering knowledge."

3.6 Areas for Improvement

For the Fundamental Needs advanced study, it will be important for additional lessons to be created beyond the wheel. Because design is for systems as well as for objects, perhaps the next lesson can be focused on the evolution of a system such as the assembly line production of the Model T. It may be helpful to engage in focused lessons that require the assessment of various assets and liabilities within a design, and to further contextualize these discussions by imagining a situation, a people, a location and a time for which the design is being created. This will likely lead to a deeper appreciation of the sophistication of even very 'simple' designs.

4 The Role of the Sensorial While Teaching: Science's Relationship to Engineering

The narrative power of the Five Great Lessons provided context and motivation for children, but that is only the beginning of the Montessori method of instruction. Key sensorial activities are needed to help students explore the world, which they do naturally, and connect these experiences with underlying truths and concepts.

4.1 The Existing Montessori Framework

The Story of the Universe was used to demonstrate the distinction and interrelationship between science and engineering. A design challenges was created to allow students to explore the underlying realities of the world (in this case, the Laws of Motion) and the engineering design process.

Although sensorial experiences are an essential part of the Montessori system, creating a meaningful sensorial experience is non-trivial. Some children (and adults) are naturally or innately attracted to it. Others are not but could be engaged if the opportunities to get involved were made available. Some of this experience evolves into an understanding of how things *happen or work*—falling objects, wheels on a road, machines, etc. These experiences are the foundation for understanding physics. Since engineering is the application of science such as

physics to meet a need, it was important for the teachers (and their children) to have some of that foundation to get started. Hence, we emphasized physics early on.

4.2 The Engineering Connection

Many engineering projects require understanding of the Laws of Motion, usually developed more intensely in the pre-requisite physics course required of all engineering disciplines. If students at an early age could be exposed to experiencing and analyzing physical phenomena, it would help future instruction. The importance of experience was a guiding philosophy for the course instructors. The Montessori system placed importance on sensorial experience in each of its lessons, and engineering as a profession required experience (not to be replaced by education) in order to be licensed.⁷

4.3 Motion 3-Part Cards: Using Montessori Taxonomy Instructional Methods

In order to develop a foundation of physics principles that could be applied through activity, we provided language (taxonomy) about the kinds of motion (e.g. linear, rotary, reciprocating) and how one motion (rotary motion of a wheel, for example) can produce another motion (linear motion along a road) through mechanisms and machines. Two cards were made to help connect the motion name with the schematic of the motion. The third "card" was an object that illustrated the motion type (e.g. a wind-up toy). This was a simple yet foundational way to tie sensorial experiences to more abstract concepts.

Transferrable Educational Element: Terminology is an important part of the expert communication process. However, instead of jumping to overly verbal definitions, the sensorial three-part card method helps children associate the real world experience with the term and the schematic representation. When children are able to converse intelligently and identify examples in the real world, they have the building blocks necessary for more complex and abstract ideas.

4.4 Mabel Marble: Using Montessori Narrative in Sensorial Lesson

Because we were designing a curriculum for children from 1st through 6th grade, we needed stories to inspire children and to illustrate concepts. We also needed an organization that spiraled to allow teachers to build concepts over time. These sensorial experiences would lay the foundation for understanding the more abstract concepts such as Newton's Laws of Motion.

One particularly successful activity was called 'Mabel Marble.' Using an inclined plane, students (teachers or their children) are told the story of Mabel, who lives at the top of a great hill (Point A). One day she saw her grandmother coming from across the field at the bottom of the hill (Point B). Her grandmother stopped to wave at her in the same moment that Mabel went racing down the hill to embrace her (for she hasn't seen her grandmother in a great while). Our challenge to the students: How can we make sure that Mabel will meet her grandmother with a gentle kiss, rather than racing by her, stopping short, or crashing into her?

Transferable Educational Elements: The Engineering Design Process (EDP) is introduced as a framework for meeting a human need. The level of usage and exploration differs based on the

age of the child. For early childhood, EDP is explored indirectly. Children learn about a need, the 'problem' associated with that need, explore options and then design a solution that is limited by certain constraints, find one (or more) solution that solves the problem, and finally propose and test that solution, refining as needed.

Development continues with the six-year-old child moving from the story about Mabel and her grandmother to attempting to design a path along the inclined plane that will bring Mabel to grandmother with nothing more than a slight touch. More complex constraints are introduced: only one level of incline with the board, no barriers behind 'Grandmother' to stop Mabel, one basket of materials (including erasers, felt cloths, cotton balls, clay and a few other materials), and a set beginning point (Grandmother can be place anywhere off the inclined plane).

In lower elementary (grades K-3), the story is presented to the children and then the follow-up activities help the child learn to isolate the variables that affect the situation. In the first lesson, children are invited to explore the difference in Mabel's speed as the surface of the inclined plane is altered with felt, silk, burlap or other materials (sensorial experience with friction). The next lesson allows children to explore the effect of altering the height of the incline (sensorial experience with height). In both cases, quantification is possible, and from this data predictions can be made and conclusions drawn. Other variables give sensorial experience to complex factors: using popsicle sticks on the surface of the inclined plane, creating a 'switchback' path, altering the marble with tape or clay, using a larger or a smaller marble, and so on.

Following these experiences, students are also able to use Mabel's story for an initial experience of quantifying speed. In these lessons, children measure how far the marble travels in a fixed time (5 seconds, for example). At this level, the Mabel Marble lessons are preparatory for the physics work children will do with the inclined plane using a Hall's carriage and various weights in the upper elementary grades (grades 4-6).

In the upper grades, measurements, calculations, graphing and prediction are included so children see the interrelationship between mathematics and engineering and refine their understanding of the way the world works. As more detailed control of variables and calculations are introduced, the foundations for scientific inquiry are laid. In addition to the lessons explored above, pictorial charts were created to help children bridge experiences with the laws of motion that govern their everyday lives to the same laws of motion that govern the movement of the planets and stars above. A pivotal lesson entitled "From Mabel to the Moon" connects basic physics principles to both planet and person.

4.5 Findings from Using Montessori Sensorial Elements

For those students who need a purpose for their lessons, the early engineering exposure gives a context and sensorial experience to draw upon when doing future physics experiments. An appropriate design challenge leverages engineering for purpose and science for discovery of natural phenomena. Teachers noticed the following as they incorporated these lessons into their classrooms:

- Sensorial Experiences Needed More Guidance at Younger Ages: Teachers in our program discovered early on that children struggle with the concept of altering only one variable at a time. When multiple variables were altered, children were not able to use the observed alterations in the marble's path to modify their design. Instead of engineering, they were tinkering randomly and fruitlessly. Carefully structuring the lessons and experiences allowed the children to gauge the effects of specific changes more accurately and therefore modify their designs more effectively. In essence, the teacher had to use the engineering design process to guide students' learning. Though the engineering design process to problem solving.
- Narrative Appealed to All Students: The Mabel Marble lesson in particular was extremely popular and successful across all classrooms. Young children had a special love for the story—but even older children enjoyed the story and the challenge of bringing Mabel to 'lightly kiss' her grandmother. In the year following the introduction of this lesson, it remained a cornerstone lesson that was greatly responsible for children's cheers of delight when the engineering lessons were started. We are still waiting to find out the full results of the students with the full three-year exposure. A representative observation was:
 - "Engineering speaks to children; they could hardly wait for the engineering lessons. They would hurry to finish their other work so that they could figure out another path for Matilda (sic) Marble [engineering lesson]. I appreciated the problem-solving aspect of some of the lessons and I will be using this more in my teaching in general."

4.6 Areas for Improvement

One aspect that will be improved in future work with these lessons is the emphasis on the iterative nature of the design process. It is important for teachers and children alike to understand the difference between engineering and 'tinkering.' The very young children seem to mostly tinker in this activity, rarely using a logical method for modifying their design. Teachers in the field found that they needed to break the lesson into several experiences, isolating the variable to be altered and allowing the children to work within this constraint. This more controlled approach seemed to help the children order their thinking and fostered deeper understanding of how each alteration impacted the speed or direction of the marble.

From this first phase of implementation, we believe that the more experience children have exploring and testing (e.g. moving objects up and down an incline), the more natural and sophisticated their ability to test and predict will become. This in turn leads to a more well-developed ability to design.

After watching teachers implement the engineering lessons at various levels of elementary and middle school, the course instructors realize that the next iteration of this course needs a culminating experience that brings the sensorial, design, inquiry and quantitative elements together again. This may come in the design, testing, redesign of a Rube Goldberg, a wheelchair ramp, and/or a hand-powered automata incorporating machine, motion and force elements

experienced. If designed properly, these opportunities will also develop and mature children's ability to problem solve in real life.

5 The Learning Spiral in Evaluation: Using EDP to Propose Viable Solutions

The intellectual aspect of the Mabel Marble activity was deepened by the many levels of engagement for children as they were re-exposed to the lessons and given more complex follow-up assignments. In this section, we will describe how this spiral of lessons and challenges are used to evaluate student progress from sensorial to abstract concepts.

5.1 The Existing Montessori Framework

Currently Montessori classrooms are arranged in three-year age groupings: 3-6 year olds, 6-9 year olds and 9-12 year olds. The middle school students were 12-15 years old. Children remain in a classroom for three years, moving from being a younger student in need of help and guidance by their peers to an older student, well versed enough in classroom routines, expectations and curriculum to support the younger students. As a result, all Montessori curriculum is designed to allow one activity to explore many levels of inquiry.

In the Mabel Marble lesson, the teacher works with students of varying levels on developing essential experiences for both science and engineering. In early childhood, this lesson can be used as a sensorial experience of motion, initial experiences with inclined planes, learning to design within constraints, and as an introduction to the concept of a 'designed solution.'

Given the proper assignment, elementary students can explore variables in experiments, learn the kinds of motion and the basic laws that govern them, and discover the trade-offs often inherent in design solutions (there is no perfect design).

The older elementary and middle school children are then challenged to attach mathematics and quantification such as speed, work and effort to the experience, graph results and use the graphs to predict beyond the limits of the activity. They also extrapolate beyond the sphere (marble) to wheeled objects which introduce many more design variables.

5.2 The Engineering Connection

This spiraled evaluation method can be used for more complex and traditional engineering problems. The engineering design process is the perfect lens through which to explore the more abstract thought process behind the design. Engineering offers, again, the opportunity for deep critical thinking and inquiry.

5.3 Building an Empire: Using the Montessori Fundamental Need in the Learning Spiral

The lesson begins with the design criteria as presented by a (fictitious) roman emperor. The roads leading to Rome from all areas of the empire must be built and made secure from attack. Because the Roman Empire is vast and hilly, many bridges must be constructed to span valleys.

The criteria for the bridges are introduced as follows:

- Construction must be relatively cheap
- Material must be plentiful across the empire
- Structure must be relatively simple to build
- Structure must be strong, durable, stable & resistant to destruction

The lesson goes on to explore two possible material resources: wood and stone. Each is discussed and researched based on the criteria, and finally stone is selected. This sets the stage for the next lesson, how to actually build a bridge out of stone.

Transferable Educational Element: Using narrative to transfer human need to an engineering problem provides the context to engage, motivate and propel learning. As students mature, the lessons must be framed to go beyond these early stages, combining story context and sensorial experience with thinking skills.

5.4 The Roman Arch: Using the Montessori Spiral Learning Model

Before a bridge design can be understood, some more foundational definitions and experience are needed. In fifth and sixth grade, students work with concepts of materials and structures. We begin with a study of the five forces (bending, compression, tension, shear and torsion). This is followed with a study of materials, their properties, and their reactions to the various forces. Sensorial experiences are leveraged: Using spaghetti and clay to make a 3 dimensional model of a pyramid and a cube, students compare the forces that act on the two structures and compare their ability to handle the force. This lesson underscores the stability of the triangle shape in design. Several variations of trusses are explored, and students are challenged to design a chair out of spaghetti that can hold 10 times its weight for at least 5 minutes.

After many experiences with materials and structures, the analysis of structures and the forces that act on them is more formally introduced using the Roman arch. In many ways this lesson synthesizes many of the engineering concepts that have been built up over time: the organization of the lesson follows each major step in the engineering design process, the structure itself fulfills two Fundamental Needs (transportation and defense), the forces and material properties are analyzed, and human ingenuity is celebrated.

A model (prototype) of a roman arch is built out of wooden blocks. Each part of the roman arch is identified and named since another significant aspect of Montessori education is the integration of accurate nomenclature. The design of the arch, its assets and liability are explored. The idea is tested by applying expected forces. We notice that the haunches take much of the horizontal force, leading to a discussion about how the forces travel and also what this means for our design criteria.

We then evaluate the results and what we have learned: adding more weight increased the compression, holding the walls together even more tightly; and removing elements of the haunches compromised the integrity of the overall structure.

Finally the students propose the final design of the bridge, complete with the reasons behind each

element as determined from their experiments and analysis of the problem. Common elements of any design will suggest:

- Use arch made of stone (span is still limited, but strength is greater)
- Create strong and stable piers and haunches
- Include frequent piers
- Learn about construction technology to know how to build in river beds
- Include abutments at either end of the structure to bear the weight of the force moving through the haunches

Transferable Educational Element: This activity is a culmination of a number of different concepts. While this lesson clearly reflects a 'led discussion' rather than a free design experience, it allows the student to see how the whole design process brought to bear on a particular problem for which a brilliant solution was devised. It also models more sophisticated engineering practices where engineers have a good idea of what will work before they actually build it. The student, with the experiences of forces, materials and structures behind them, can now unlock the genius of this designed solution, while also engaging in critical inquiry about its assets and liabilities.

5.5 Findings from Using Montessori Elements of Learning Spiral

While these lessons bring children closer to more traditional engineering problems, the richness of the lesson teach more than discrete facts and skills.

- More Complex Problems Develop Higher Level Thinking. The lesson described above is a higher level exploration of the student's earlier work with the initial concepts of human needs, as presented in the lower elementary. Engineering is brought in at the upper level to deepen the inquiry and offer a new lens through which students can understand differences in design.
- The Engineering Design Process Can Play a Key Role in Higher Level Thinking. To understand much of human history we must learn from the cultural artifacts that remain. Through these artifacts we can reconstruct a thought process that clearly connects closely to the engineering design process. Seeing design through time we are suddenly struck with the knowledge that many the tools and technologies that we take for granted have all required this kind of design mentality to become as useful and practical as they are. Engineering is, truly, all around us all the time. As one teacher observed, incorporation of engineering informed her whole teaching practice:
 - "It fits so well with Montessori. It just fit really well the way we think about designing materials and tweaking materials. I had those moments with engineering where you get into discussions and you can't stop talking about it. My ability to discuss that area of science has expanded which means I can discuss it with my students and I have a better understanding. I can incorporate it into my teaching and I think that was successful."

5.6 Areas for Improvement

A future experience would add the analysis of other structures, along with a list of significant structures from which to choose (gothic cathedral, for example). Students will then create a presentation that follows the engineering design process as modeled with the Roman arch.

6 Conclusions and Discussion

The Montessori expert felt that engineering helped the teachers in the course understand the power of an intentional design process. It was something they could use in developing curriculum, class systems, and any other opportunity to problem solve. They were also able to engage the students in designing solutions both through the new course work and lessons as well as through the process of creating solutions to classroom routines.

Another benefit engineering offered the Montessori educator (and all educators) is the idea that no design is perfect. It encouraged them to begin with something, to get engaged and to worry less about some idealized notion of 'perfection,' and rather to consider that design, as an iterative process, offers the potential of ongoing design improvements. The best thing to do is simply start.

Working within the Montessori educational framework was both challenging and enlightening for the engineering expert. Interestingly, the most valuable lessons for the engineering expert arose from the non-negotiable constraints of the Montessori system:

- **The Power of the Narrative.** It is a bit awkward as an engineer to start a lesson with "Once upon a time" but the power of this framework was amazing. Teachers who had been petrified of learning engineering became engaged, confident, and intrigued. Children they taught benefited from the purely positive wonder introduced by this narrative approach. It was an eye-opening experience for the engineering expert of the team.
- The Importance of the Sensorial. As an educator who has studied women in engineering, the engineering expert knew of many anecdotal cases where women did not believe in their competence because they lacked specific hands-on experiences. Few of them, compared to their male counterparts, had the machine-repair, tool, and hand-eye experiences that is so foundational in engineering projects and courses. Engineering was publicized to them as simply a combination of mathematical ability and scientific knowledge. In college, however, sensorial experiences are not taught, but are expected in both physics and engineering classes. On one side, it was satisfying to hear how important Montessori viewed sensorial experiences in understanding concepts in a deeper way. On the other side, it was enlightening how exposure could be specifically designed to enhance the larger understanding of concepts that later be quantified in college level physics and engineering courses.
- The Craft of the Learning Spiral. As a college educator, it was instructive for the engineering expert to see how the Montessori expert discerned the essential lessons from typical engineering lessons and then scaffolded the desired objectives into specific

assignments. It underlined the importance of working with someone outside of the field since being an expert in the field sometimes curtails one's ability to break the learning into smaller parts.

The lessons, embedded in the MSTEM album, are a good start at developing the foundations of engineering in the Montessori program at the early childhood and elementary levels. The next step is to further this foundation at the middle school levels by refining the science and mathematics lessons to bring the engineering process to a higher level of rigor and sophistication.

The journey has just begun.

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