The Renaissance Foundry:  
A Powerful Learning and Thinking System to Develop 21ST Century Da Vinci Engineers *

Pedro E. Arce¹, J. Robby Sanders¹, Andrea Arce-Trigatti², Lacy Loggins¹, Joseph J. Biernacki¹, Melissa Geist¹, Jennifer A. Pascal¹, & Kenneth Wiant¹

Abstract

The Renaissance Foundry Model, a pedagogical framework is based on innovation-driven learning that can transform traditional STEM classrooms into creative environments for student learning. The model is based on two key paradigms: the Knowledge Acquisition Paradigm and the Knowledge Transfer Paradigm. These two paradigms help students to take a Learning Challenge and move it, through a series of steps, towards the development of a Prototype of Innovative Technology which becomes a possible solution to the challenge. In addition to these paradigms, elements of the model, implementation strategies, assessment and suggestions for further implementation are presented and discussed. A case study at the Chemical Engineering Department of the Tennessee Technological University is used as an example for illustrative purposes.

Key Concepts

- The USA National Academy of Engineering (2005) call for a 2020 new and more creative professional model in engineering is an impetus for development of the Renaissance Foundry.
- The Foundry is built on active and collaborative learning approaches, in particular, the High Performance Learning Environment (Hi-PeLE™) approach incorporating a Group Genius style approach for achieving maximum creativity in a collaborative learning environment.
- The Knowledge Transfer Paradigm is a very efficient way of providing a successful path for students to reach the highest level of mastery learning (i.e. creativity) as outlined in Bloom’s Taxonomy.

Key Words

Innovation-driven learning; adaptive expertise, prototype of innovation, team-based learning.

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¹Tennessee Technological University Department of Chemical Engineering ²University of Tennessee-Knoxville Department of Educational Psychology & Counseling ³Algood Middle School, Putnam County, Algood, TN ⁴Tennessee Technological University Whitson-Hester School of Nursing ⁵Tennessee Technological University, College of Business

Corresponding Author:
Pedro E. Arce, PhD, Professor and Chair of Chemical Engineering, Tennessee Technological University, Cookeville, TN 38505  Email: PArce@tnitech.edu
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Introduction

Currently, engineering is a very successful profession with an excellent demand for jobs and very appealing starting salaries.¹ Thus, from a common sense point of view, why would anyone think that changes in the current professional profile of a graduating engineer are needed? The reason lies with the challenge of being successful engineering pioneers in our current global economy. The characteristics of our global economy reflect a shift from a primarily manufacturing based paradigm to a knowledge based paradigm, and now towards a creativity-based paradigm where innovation-based technology and business play a major role (Christensen, 2011). Consequently, in order to stay ahead of the economic competition, our global economy demands that engineering professionals be globally and socially conscious service people, technological entrepreneurs, and multidisciplinary revolutionaries: in effect, innovators in their fields (Boekhoff, 2006; Lucena, Downy, Jesiel, & Elber, 2008). A recent economic report released by The White House (2011), illustrates this call for innovation within our workforce:

Other countries understand that innovation is fundamental to their economic well-being and are finding new ways to advance their innovation agendas. We can be even more ambitious, even more successful, and even more focused on building the essential sidewalks of innovation (p. 5).

Although there are other factors, the presence of creative individuals has been indicated as a potential factor for fueling innovation (Moretti, 2012). For example, Florida (2007) used the presence of creative individuals as a possible reason for the presence of “spiky” regions of innovation such as the Silicon Valley-like cities (e.g. San Jose, California; Seattle, Washington; Austin, Texas; and Minneapolis, Minnesota, among others) that are playing an important role in bringing disruptive technology to life (Christensen, 2011).² An additional, useful example is the Innovation Park at Purdue University that is currently the largest and one of the most proficient at generating new technology in numerous fields.³ Thus, although the knowledge economy has been the driving force for years in economic development, it is giving way to the “Creative Economy” which promotes group interaction, as well as hands-on and minds-on

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¹The average starting salary for graduates of the undergraduate programs based on Tennessee Technological University Career Services is as follows: Computer Science: $64,100; Chemical Engineering: $66,900; Civil Engineering: $58,000; Computer Engineering: $70,300; Electrical Engineering: $62,500; Engineering Technology: $60,900, and; Mechanical Engineering: $63,900.
²“Disruptive” here is used to indicate a new technology that completely replaces a popular one. For example “mobile phones” were a product of a disruptive technology for the fixed-line phones (Christensen, 2011).
³See http://purdue.edu/discoverypark/.
development (Duderstadt, 2008; Organisation for Economic Co-operation and Development [OECD], 1996). From this brief overview, it is clear that the relevance and impact of the need for a paradigm change in engineering education is imperative; it is also beneficial for both the production of a more innovative and creative individual as well as for impacting communities through effective entrepreneurial efforts. Recommendations for these types of paradigmatic changes are suggested in recent initiatives released by the USA National Academy of Engineering (NAE). To illustrate this point, in its 2020 Engineering Model, the NAE championed analytical and logical skills contextualized in socially compelling challenges (Committee of the Engineer of 2020, 2005; National Academy of Engineering [NAE], 2005). According to this model, new engineers should have a social and global understanding of the profession and how this interfaces with entrepreneurship opportunities that attempt to make healthy impacts on their community (Committee of the Engineer of 2020, 2005; NAE, 2005).

The pith of this paradigm change lies in the following: within the traditional (i.e., the “knowledge-based”) engineering education paradigm, skillful conductors, who are very capable of maintaining processes and efficiently running production, are produced. However, the new engineering education paradigm discussed herein addresses the demands of the creative economy paradigm by creating composers, instead of conductors, who can learn (on the job) the traits of innovative approaches to safe energy, the engineering of greener products, and the effective marketing of these new technologies, inter alia (Arce, 2009). Therefore, a more efficient way for engineering schools to satisfy the demand from the world market is to produce a composer-style engineer that hits the ground running with many of these desirable characteristics and that will not depend on established companies to produce technology innovation (Arce, 2009). In fact, this engineering professional will generate innovative technologies that will eventually complement existing ones or, alternatively, will replace them. In summary, the development and placement of the composer-style engineer, or alternatively called a Da Vinci-Style Engineer, can play a significant role in the generation and implementation of innovative technology. As such, the schools that are more efficient in their development of such engineers will undoubtedly play a major role in developing this new economy.

In this contribution, the co-authors present an overview of the reasons supporting the development of the innovation-driven learning approaches that led to the generation of the Renaissance Foundry and provide examples of methodologies that have been effective in the development of Da Vinci-style Engineers. In particular, the efforts in the Department of Chemical Engineering at Tennessee Technological University (TTU) are highlighted and lessons learned are illustrated. In addition, this contribution presents a preliminary discussion of the broader impacts of a Renaissance Engineering model such as the one adopted by the College of Engineering at TTU for its strategic plan.

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4 See http://www.nae.edu/Programs/Edution/Activities10374/Engineerof2020.aspx.
Innovation-Driven Learning:  
Necessitating Reasons, Guiding Principles, and Useful Methodologies

As discussed in the introduction, education must adapt and anticipate the challenges facing our future generation. Currently, our challenges are increasingly concentrated in advancing science and technological topics, including making solar energy economical, the development of sustainable fuels, and affordable quality healthcare, among others (DeBoer, 2012; NAE, 2010). In addition, the global economy, driven by the needs originated in different countries, requires not only literate professionals, but socially- responsible leaders who can adapt their expertise to address the disparate needs (e.g., utilization of regional resources or the quality of healthcare) of communities across the world (DeBoer, 2012; Felder, Brent, & Prince, 2011). To illustrate this point, according to the Continental Global Engineering Excellence Initiative released by the Continental Corporation (one of the leading international automotive suppliers), “in a globalized world engineers need skills that go far beyond what is traditionally considered necessary,” including entrepreneurship, cultural sensitivity, and resource flexibility (Boekhoff, 2006, p.3).

Thus, the challenges that face our current labor force are continuously requiring more complex and adaptable skill sets that integrate interdisciplinary knowledge into the traditional hard sciences (Accreditation Board for Engineering and Technology [ABET], 2013).

As hitherto indicated, innovation has been identified by leading political and economic leaders as a conceptual skill set necessary to better prepare engineering professionals to address these challenges. In a recent report released by the White House, President Obama declared:

The United States led the world’s economies in the 20th century because we led the world in innovation. Today, the competition is keener; the challenge is tougher; and that is why innovation is more important than ever (The White House, 2011, p. 1).

The creation of the World Bank Institute’s Knowledge Economy Index, which gauges a nation’s innovation level among other knowledge-based skills, has further raised the consciousness of the importance of innovation in tackling larger societal and technological issues (DeBoer, 2012; OECD, 1996; World Bank Institute, 2007). Moreover, the concept of innovation has spread to the field of foreign aid with the Science, Technology, and Innovation (STI) Team of the World Bank calling on innovators, “to solve, transform, and impact” impoverished communities around the world (The World Bank, 2008, p. 44). As illustrated by these examples, innovation – new ideas, original research, and entrepreneurial concepts - is essential to pioneer the advancements of the future with the engineering field.

In order to develop this innovation, a paradigm change, as previously indicated, is needed, particularly within the engineering education methodologies. For example, the traditional methodology to develop an engineer is focused on a top-down approach where the instructor is the source of infinite knowledge and conveys this knowledge to the students (i.e. at the bottom of the skills scale with a supreme authority) (Arce, 2006; Feynman, 1992). No recognition is given regarding the knowledge that students bring to class and whether this is a misconception or, contrary to the usual instructor’s beliefs, a useful foundation to build new concepts and skills (Bransford, Brown, & Cocking, 1999). Further, no opportunity is provided for the student to
discuss new ideas that, although they may be rough prototypes, could be excellent sources of innovation (Arce, 2006; Felder, 2012).

In fact, the characteristics of the current engineering education approaches largely used in programs within the United States are contrary to the suggestions made by leading experts in pedagogical learning (Boekhoff, 2006; Bransford et al., 1999; Felder, 2012). In short, there is little opportunity to focus on the student’s transformation from a novice to an expert learner (Arce, 2010). Paraphrasing a phrase from a 1959 Caltech presentation by Richard Feynman (1992) on nanotechnology, there is ample opportunity at the bottom of the scale (p. 61). In the context of education, this means there is opportunity to focus on the students as prototype learners and upscale them into efficient learning individuals; in effect, this will allow students to be skillful in both acquiring knowledge and transferring this knowledge to new situations ultimately fostering innovation. As Steve Jobs (2005) posited in a Stanford University commencement address, innovation is about connecting the dots, specifically in a novel and unique way that has not been done before. This connection of dots seems to happen more efficiently at the transfer of knowledge (or adapted expertise) level after the individual has reached a competitive level of knowledge and skills acquired in the subject (Jobs, 2005; McKenna, 2007).

In general, experts agree that while these conclusions (on collaborative, active learning and innovation-driven approaches) are widely supported across disciplines and various levels of education, teaching strategies that incorporate metacognition and true inquiry are not commonly practiced in classrooms due to the high level of complexity, time, and investment required (Beavers, 2013). However, the Renaissance Foundry Model, developed by the team of professors and students at TTU, “provides a model by which these strong pedagogical principles of active student engagement, critical thinking, and creative problem-solving may be infused into the classrooms and departments across education” (Beaver, 2013, p.1).

The Renaissance Foundry: Elements, Paradigms, and Learning Protocol

The Renaissance Foundry is a collaborative-learning platform or, alternatively, a learning and thinking system, composed of six elements arranged in two paradigms: the Knowledge Acquisition Paradigm (A) and the Knowledge Transfer Paradigm (B) as shown in Figure 1.5 The protocol of the Foundry effectively promotes innovation by guiding students through a series of steps that starts with a Learning Challenge (1) and ends with the development of a Prototype of Innovative Technology (6). In working through these steps, students are also working synergistically within the two aforementioned paradigms (A and B).

The start and end points of the Foundry (i.e. Learning Challenge and the Prototype of Innovative Technology) are connected and are what motivate the students towards progress within the learning environment. The word “challenge” refers to an issue, problem, or need that has societal relevance (e.g. ecologically cleaning a lake of contaminants, designing a sustainable a

5 The phrase Renaissance Foundry is based on an input from Dr. Kathy Haggler, Strategic Plan Consultant at the College of Engineering, TTU.
drainage for a city, etc.). These challenges need to be connected to fundamental concepts and theories which are central to the curriculum of the student’s engineering course. Throughout the course, the students are then acquiring knowledge needed to apply to a potential solution for this challenge. This potential solution takes the form of the prototype of innovative technology which can manifest in various forms including the development of a technical device, a new mathematical algorithm, or a new fundamental theory that will contribute to the solution of the challenge identified at the beginning of the course. The Prototype of Innovative Technology is produced by teams of students and assessed at the end of the course by a team of experts (Sauer & Arce, 2004; Sauer & Arce, 2011). In effect, this process encourages students to keep their radar constantly up in order to identify the gradients of innovation within their interest areas.

As aforementioned, an effective implementation of the Foundry would start by the selection of the Learning Challenge (1) for a given course required for an engineering curriculum (Figure 1). The following step, Organization Tools (2), highlights the fundamental concepts and theories necessary to commence generating solutions for these student identified Learning Challenges. This step is primarily directed towards the facilitator of learning and entails a restructuring of the contents and strategies associated with the course and may include the development of activities such as the Jeopardy® Games (Sanders, Mbachu, & Arce, 2015) and the use of the Principal Objects of Knowledge (POK), inter alia (Arce, 2000). In addition, the course syllabus organizes the key theories and fundamentals needed for the students to identify and solve the challenge.

Once the Learning Challenge and the Organization Tools are established, the Foundry shifts to focus on developing student knowledge in an effort to build a solid understanding of the
potential Learning Challenge. This step is driven by the Knowledge Acquisition Paradigm (A) which employs Learning Cycles and Cycles of Documentation (3) that are enhanced by the utilization of Resources (4). The Foundry uses different types of Learning Cycles including STAR Legacy and Research and Development, among others (Anthony, Geist, Pardue, & Abdelrahmen, 2010). The main purpose of this step is to gather and analyze available data which is relevant to various aspects of the challenge and progress students towards a viable, innovative solution (Donovan, Bransford, & Pellegrino, 1999). The Resources (4) step works in parallel with the Learning Cycles by facilitating student learning through exposure to sources of expertise which optimize and guide student efforts (Arce & Schreiber, 2004). These Resources can take the form of the following: facilitators of learning, experts (e.g. faculty, practicing-professional engineers, vendors, business executives, inter alia), peer influence (e.g. teaching assistants, classmates, inter alia) and others sources of knowledge that will engage students in enhancing the technological creativity of their ideas (Arce, 2014). In general, the Knowledge Acquisition Paradigm of the Foundry is focused on developing the understanding of the fundamentals, theories, and skills needed to resolve the Learning Challenge.6

Once the level of knowledge related to a given Learning Challenge is enough to have a clear understanding of the challenge, then the focus switches to activities driven by the Knowledge Transfer Paradigm (B). This paradigm is centered on the Linear Engineering Sequence (LES) (5) and again, enhanced by the utilization of Resources (4). LES is a series of steps that the students, or team of students, follow to end up with a Prototype of Innovative Technology (6), the final step of the Foundry (Arce, 2003; Arce, Biernacki, & Melton, 2006). Figure 2 (a) lists the key steps involved in LES while Figure 2 (b) illustrates the process of moving from a Learning Challenge to a Prototype of Innovative Technology within this paradigm. In particular, Figure 2 (a and b) lists the key steps of the sequence and how these steps work together to guide the students through an innovation process. This process involves both identifying the pieces (dots) of a possible solution pathway to the Learning Challenge and then connecting these pieces (dots) to efficiently design and build a Prototype of Innovative Technology (Jobs, 2005). The LES thus acts as a sequence in the sense that it starts with the adoption of a Learning Challenge and finishes with a Prototype of Innovative Technology that is suitable as a solution to that challenge. Ultimately, LES mimics the classic assembly line for cars introduced by Henry Ford; here the Prototype of Innovative Technology plays the role of the car being assembled (Alizon, Shooter & Simpson, 2009). In this assembling process, every effort of the student or student team must move the prototype (i.e. the “car”), towards the end line at the conclusion of a given semester.

Within the Renaissance Foundry (Figure 1), LES is an adapted expert outcome of Jobs’ principles of innovation (Gallo, 2010). Therefore, the LES is a crucial Foundry element because it focalizes innovation as a central component within the student learning environment. From the

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6 For example, if the course challenge is devices that measure flow rate (i.e. flowmeters), then the fundamental theory of fluid mechanics and experimental skills are important in identifying an innovative flowmeter prototype.
point of view of innovation, the implementation of the LES is more effective after the student has reached a mastery level of knowledge and skills attained within the Acquisition of Knowledge Paradigm of the Foundry (Figure 1). Bloom’s taxonomy provides a cognitive outline for this assumption: creativity is the top cognitive level that can be reached only after the student has successfully mastered five prior levels of knowledge acquisition (Anderson et al., 2001). Thus, prior to having a sufficient level of knowledge concerning the Learning Challenge, the student will not be able to effective move from Learning Challenge towards the final objective of creating a Prototype of Innovative Technology. However, the LES does not preclude that students and instructors use Learning Cycles in discussing and implementing outcomes that are useful for generating ideas regarding the Prototype of Innovative Technology (Martin, Rivale & Diller, 2007). Instead, Learning Cycles are complementary to such activities where innovation can be further enhanced by advancing the processes for solving Learning Challenges.

Furthermore, within the LES, students, working within teams, are coached to use a collaborative learning, or “Group Genius”, environment in order to maximize the level of innovative aspects concerning the Prototype of Innovative Technology (Sawyer, 2008). As an additional step to fostering innovation, entrepreneurial elements are integrated into the creation of a Prototype of Innovative Technology. These elements encompass the following: students are required to produce a business plan for their Prototype of Innovative Technology (e.g. costs of production) and research preliminary market forecasts for the transfer of their technological innovation into that market. This aspect is conducted in collaboration with the TTU College of Business. Effectively, the Renaissance Foundry displays several complementary components that work synergistically and efficiently to implement Jobs’ innovation principles (Gallo, 2010).

The pedagogical engine of the Renaissance Foundry (Figure 1) is based on the High Performance Learning Environments (Hi-PeLE™), which places students in the driver’s seat of learning (Arce & Schreiber, 2004). The Hi-PeLE™ philosophy indicates that, “...every time that an instructor-based explanation is replaced by a student-based activity, we are bringing an effective learning environment to the students” (Lykins, 2010, p.1). Therefore, instead of students being assigned problems to solve (a passive learning approach), they are coached through a process of innovation that requires that they identify a societal need (i.e. Learning Challenge) and develop a solution (i.e. Prototype of Innovative Technology) by transferring the knowledge acquired in the course (an active learning approach) (Creighton, 2001). Such an approach empowers students to recognize that they can contribute to solving complex societal issues even as students. Further, this approach is focused on developing Da Vinci-style engineers – or more generally STEM professionals – capable of transferring his/her knowledge to solve challenges not previously encountered (Arce, 2012).

Case Study: The Department of Chemical Engineering, Tennessee Technological University

During the last several years, faculty and students from the Department of Chemical Engineering at TTU created, implemented, and assessed the Renaissance Foundry. The Foundry was created to
be an effective educational system geared towards developing the new Da Vinci-style engineer along the lines of the USA-NAE 2020 Engineer Model (Committee of the Engineer of 2020, 2005; NAE, 2005). This new, cutting-edge platform is having a major impact by changing the curriculum and culture of the department; in turn, these changes have allowed the Chemical Engineering program at TTU to be positioned among the leaders within the country in innovation-driven learning (Miletic, 2014). The following sections provide robust, evidentiary support for the new platform with descriptions of basic characteristics, results and assessments of the implementation, and lessons learned. In order to introduce a chronological perspective of these efforts, the description below is divided in the following phases: initial roots and impetus, transformational years, and adaptive expertise years.

Background

The Initial Roots and Impetus for the Foundry. In 2003, at the time when Arce joined the Department of Chemical Engineering at TTU as Chair, the department was losing ground on several fronts. Enrollment was very low (less than 100 students), hiring was not at its best with major companies not coming to campus to consider chemical engineering graduates, the curriculum was antiquated, and most of the teaching was centered on traditional, or passive
methods, such as the lecture-homework-quiz method (Loggins, 2012). After a decade of innovation and transformation, the department has increased the undergraduate student enrollment to 357 students and 34 graduate students (as per Fall 2014) and yields the largest number of female engineers (per year) among the departments organized within the TTU College of Engineering. Figures 3a and 3b illustrate the enrollment growth of the department at both the undergraduate and

![Figure 3a. Chemical Engineering undergraduate student enrollment 2002-2014](image)

![Figure 3b. Chemical Engineering graduate student enrollment 2002-2014](image)
graduate levels. Additionally, the department enjoys one of the highest student retention rates at TTU, has received the longest period of accreditation possible, both at the undergraduate and graduate program levels, and its faculty has received important university, regional, and national distinctions (see Broader Impacts).

These enrollment, graduation, and retention numbers have consequently helped the department to achieve regional and national recognition for the pedagogical and leadership approaches utilized to garner these results. Further, the department’s efforts in curriculum modernization have been recognized by a number of awards at the university, regional, and national levels (see Broader Impacts section). In addition, the department has become one of the largest Departments of Chemical Engineering (based on undergraduate enrollment) among all public institutions within the State of Tennessee (American Society for Engineering Education [ASEE], 2013). This impressive status can be attributed to several complementary factors, with the foundation rooted in the novel and dynamic characteristics of the curriculum, faculty, and staff. Within this process of change, the Renaissance Foundry and its pedagogically powerful engine, the High-Performance Learning Environment (Hi-PeLE™) have played a major role (Arce & Schreiber, 2004).

**The Transformational Years (2003-2007).** Immediately upon his arrival, Arce began to work in collaboration with Biernacki (TTU University Distinguished Faculty Fellow) and Visco (the current Associate Dean of Undergraduate Studies for the College of Engineering at the University of Akron), on identifying transformational approaches to advance and modernize the curriculum. One of the key goals was to bring collaborative and active learning pedagogical methodologies to the forefront. Among these goals were the integration of classrooms with laboratories and the realignment of the transport phenomena courses associated with the curriculum known as the transfer science sequence. In parallel, Arce worked with other collaborators to develop an efficient approach to knowledge acquisition and the application of this knowledge (not necessarily the innovative transfer of knowledge) to various engineering scenarios, all of them carefully selected by the instructors, or facilitators of learning. The approach was pedagogically innovative since the students, and not the instructors, were placed in the driver seat. Such an approach was termed the High Performance Learning Environment (Hi-PeLE™) and is, in actuality, an implementation of the philosophy Arce published in collaboration with Loren Schreiber at the Florida State University (Arce & Schrieber, 2004). During this early period (2003-2007), no innovation-driven learning was part of the Hi-PeLE™ although the evolution was a natural platform upon which to build the Renaissance Foundry as shown in the next section.

**The Adaptive Expertise Years (2008-Present).** Following the implementation strategy described in the section above, students and collaborators at the TTU Department of Chemical Engineering worked on an adaptation strategy that finally led to the Renaissance Foundry model. Consequently, the Foundry is an expert adaptation from the Hi-PeLE™ with the primary purpose of introducing an innovation-driven approach to student learning. Based on the collected evidence described in this contribution, the model is a powerful and pedagogically efficient “engine” to develop the 21st Century (STEM) Da Vinci-style Professional along the lines of the USA-NAE 2020 Engineer Model (Committee of the Engineer of 2020, 2005; NAE, 2005). In other words,
the Foundry is an effective platform to drive the formation of new (STEM) professionals who, beyond the usual, logical, and sequential attributes, are also innovators and entrepreneurs with a high sensitivity for global and societal impact. From 2008, the model has been implemented in several courses at the TTU Chemical Engineering Department and has shown promising success (see Illustrative Examples).

**Role of the Teams in the Renaissance Foundry**

The Foundry is centered on collaborative-based approaches wherein both team-based learning and organizational behaviors play critical roles. This approach provides formal teamwork training early in the course of study of the curriculum. First-term sophomores in an Introduction to Chemical and Biological Engineering Analysis course are put through a rigorous Hi-PeLE™ teamwork training workshop wherein students learn to recognize differences between groups and teams and to identify good and bad team behaviors. Students are led to discover that indeed they already know a great deal about teams and teamwork but have not had ample opportunity to engage in the types of teamwork activities that will make a difference in their careers as engineers, innovators and inventors. In these workshops, students also come to realize that team selection depends upon goals and that the best team is not a group of friends, but rather individuals that form bonds and dependencies over a period of time (Sauer & Arce, 2004). After selecting teams based on skills, students are provided a number of opportunities to test their teamwork skills on real-world, hands-on problems (Sauer & Arce, 2004). These problems are open-ended and can be solved in multiple ways that involve a range of skillsets including laboratory, mathematical, computational and communications.

Teamwork training is enhanced by a similar series of workshops that train students in critical thinking skills (Biernacki, 2011a, 2011b). Again, students are enabled to discover how to identify critical thinking and what skills are associated with critical thinkers. These critical thinking skills are then applied to both the solution of theoretical problems and in the laboratory where students must sort through situations that have multiple solutions. In a preliminary assessment of this approach, students were found to have improved (at the 95% confidence level) in their critical thinking skills after only one semester when measured using the TTU Critical Thinking Assessment Test (CAT) whereas a control group did not. These preliminary results suggest that focused training can improve critical thinking skills and, along with intensive teamwork training, is a continued focus of the ongoing Renaissance Foundry activities.

Teamwork then becomes a pervasive way of forming a fabric that is woven throughout the Chemical Engineering curriculum and binds both students and faculty in dynamic, collaborative environments. Activities identified in the Foundry are implemented using various modalities in almost every Chemical Engineering core course. Successive courses then build on this teamwork and critical thinking foundation and incorporate the prototype concept (Chemical Engineering Transfer Sequence, five courses), laboratory research (two courses, ChE 3990 and ChE 4990), product design (Biotransport, CHE 4661) and finally process design (CHE 4410 and 4420) into the Chemical Engineering curriculum. In each course, students solve open-ended, real-world
problems in collaborative teams that explore a wide range of engineering applications (Biernacki, 2011a, 2011b).

Illustrative Examples

Product Design – ChE 4661, Biotransport

This Biotransport course is a capstone of sorts in that students will have already completed a full semester of material/energy balances, heat transfer, fluid mechanics, mass transfer, and reaction engineering kinetics before taking it. The course integrates content from these classes with a focus on transport phenomena in the human body. From the very beginning of the semester, it is emphasized that it is not simply good enough to develop new knowledge, a concept that students will have become familiar with from prior Chemical Engineering courses. Engineers must be able to transfer new and traditional knowledge to solve societal and global problems (e.g. Grand Challenges for Engineering) (NAE, 2008, 2010). Identifying need is not an easy task, but the course emphasizes that there are many problems that are currently necessitating solutions and many problems that have yet to be identified. Ultimately, as mentioned previously, students are encouraged to keep their radar up.

Early in the semester, students are divided into two teams that participate in a Jeopardy-inspired, course-content-focused game. As opposed to having dollar-value categories, the categories for the game represent products (generally medical devices) that are used in a bio-based application and that utilize one or more aspects of Biotransport. After the game, each student is randomly assigned to one of the categories, and each student researches this and reports back to the class regarding what he or she learned. In this manner, each student will understand at least one of these products at some level of depth, and each student will have also received exposure to 20-30 other products (depending on class size) based on what they learned from the class discussions. This exposure is particularly important as a portion of the students are in the Chemical Engineering concentration and another portion is in the Biomolecular Engineering concentration and may therefore not have had prior experience with these concepts.

Student teams ultimately have to identify a medical need and develop a solution that involves one or more transport phenomena. Teams participate in formalized brainstorming sessions to identify the need, and at the end of the semester, after conducting design/feasibility/proof-of-concept studies, they present their prototypes to experts (e.g. engineering and business faculty, lawyers, and other experts involved in technology development and transfer). Several student teams have submitted their prototypes for the National Institute of Health Design by Biomedical Undergraduate Teams (DEBUT) Challenge; in addition, an invention disclosure to the TTU Office of Research has resulted during a recent iteration of the course.

In addition, student feedback regarding this course provided evidence of the critical thinking and knowledge transfer that is produced using these methods. When this Biotransport course was recently evaluated by students using the standard Individual Development and Educational Assessment (IDEA) course evaluation, students rated such aspects as “learning to
apply course material to improve thinking and problem solving”, “acquiring skills in working with others as a team”, and in “developing creative capacities”, much higher than all courses in the database, much higher than similar courses in the database, and much higher than all courses at TTU (Tennessee Technological University [TTU], 2009).

Application to a Junior Level Course – ChE 3121, Transfer Science II

During the 2012 Spring Semester, the TTU Chemical Engineering Department implemented the Renaissance Foundry in the Transfer Science Sequence and, in particular, ChE 3121, Transfer Science II, Fluids course. A team of facilitators of learning, including an overall coordinator, a practitioner, a graduate student assistant from the Curriculum and Instruction Department (whose area of interest is knowledge acquisition) and a student teaching assistant in the civil engineering program comprised this collaborative-based environment. The objective of the course is to learn about momentum conservation and momentum transfer with application to relevant chemical engineering systems. A total of forty-six students registered for the course that contained class activities, a complementary laboratory, and the implementation of the LES with its final objective, the Prototype for Innovative Technology.

In order to apply the LES, the following key items were used:

- Students were organized in teams following a functional based approach proposed by Sauer and Arce (2004). An agreement of cooperation was required for all the teams. This approach helps to establish accountability measures for the team members during the process of implementing the LES.
- Students were not given a topic for their prototypes; instead, they were required to identify a need necessitating application of course fundamentals to meet that need. As mentioned in previous sections, this part is inspired by Jobs’ innovation principles which posit an identification of dots and then a connection of these dots to foster innovation (Gallo, 2010; Jobs, 2005).
- They were coached on innovation-based approaches including proof of concept, prototypes, scaling, planning, scheduling, business plans, patents, etc. These approaches were all reviewed in sessions with the teams. This approach forced students to think beyond just engineering design and onto the entrepreneurial processes influencing industry demands today.
- Students needed to develop a prototype, build it, test it, collect data, analyze the data, and report all of these aspects to the assessment team. During this time, students met periodically with facilitators of learning to ensure that progress was being made (Figure 4).
- Students shared their progress with the rest of the class in organized sessions where they discussed pitfall situations that they might have encountered during the implementation of the LES. These summary-like presentations were required to be submitted and counted as a homework grade for the course. In addition, students were to share this material with the rest of the teams in order to keep them updated on progress made over time. This is a crucial part of the multidimensional communication identified in Hi-PcLE™ (Arce & Schreiber, 2004).
- All material generated by the students in their teams is required to be part of the Personalized
Class Binder for the project where efficient documentation must be kept for evaluation during the assessment phase (Rawlings, Allen, & Arce, 2005).

![Image](image.png)

Figure 4. Review sessions with the teams for the application of the LES.

The corresponding teams identified nine projects. The projects ranged from an innovative technology for the fluid delivery systems on car windshields to an efficient algorithm for controlling fluid flow in pipes. All of these projects resulted from the approach outlined above. Moreover, the prototypes were assessed by two teams formed from a total of nine experts. The instructor developed a final exam made up of questions based on all the projects presented. The outcome was a very high transfer of knowledge rate among teams even during the assessment session conducted by the experts (see Assessment Section).

Throughout the development of this effective learning environment, one important aspect of the application of the Renaissance Foundry to this course is the role played by the facilitator of learning. The function of the facilitator of learning is more along the lines of a coach and, as such, this professional must be aware of the various aspects involved in a coaching role as shown in Table 1 (Sauer & Arce, 2004). All

<table>
<thead>
<tr>
<th>Table 1</th>
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<tbody>
<tr>
<td>The Coaching-Based Model of “Instruction”</td>
</tr>
<tr>
<td>Technical Aspects</td>
</tr>
<tr>
<td>Tactical Aspects</td>
</tr>
<tr>
<td>Educational Aspects</td>
</tr>
<tr>
<td>Psychological Aspects</td>
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<tr>
<td>Training Aspects</td>
</tr>
</tbody>
</table>

Notes. This table is adapted from Creighton, 2001.
of the four facilitators of learning for the CHE 3121 course received training on the fundamental idea of the Renaissance Foundry. Moreover, activities were designed to complement each of their focused functions: pedagogical, practical, assisting with the various activities, and the overall emphasis for moving students towards the higher levels of mastery learning as outlined by Bloom’s Taxonomy (Anderson et al., 2001).

Ultimately, in order to have an effective environment that promotes knowledge transfer, it is imperative that learning environments be engaging, collaborative, and focused on making connections between fundamental principles (learned in the course) and industry or societal needs connected to the Learning Challenge. To complete the Prototype of Innovative Technology, the student teams need to design such prototypes to address the challenge within a global context and with a societal impact in mind. These elements of effective instructional design are clearly not part of the typical lecture-homework-quiz methodology (Loggins, 2012).

**Assessment Methodologies for the Renaissance Foundry**

**A Multi-Method Assessment Approach**

As should be clear from the above description, the Renaissance Foundry is a multidimensional learning environment that exposes students to a myriad of opportunities for learning and communication. In particular, these learning opportunities manifest when students interact with the facilitator of learning, the teaching assistants, other students and team members, and experts from outside the course (e.g. faculty, vendors, technicians, and pedagogical professionals). Teamwork provides another venue for learning. For a large portion of the course, students work in teams enhancing their learning through collaboration, where professional competition among teams is encouraged in lieu of competition among students. Moreover, within this type of learning environment the overall driving philosophy is student learning and, in particular, learning from each other.

An educational platform such as the one described here could be a challenge for the facilitator of learning. Indeed, the usual midterms and final exams are ineffective to assess the various aspects of the students’ activities within the platform, and they must be complemented or, even better, replaced by a combination of quantitative, qualitative, and summative assessment approaches (Sauer & Arce, 2011). In addition, the team-based learning component must be an important portion of the student grade in order to not cheat the students of the efforts they have put forward as individuals working in various team-centered activities (Arce & Schreiber, 2004).

Following this notion, during the development and implementation of the Foundry at TTU, a multi-level approach for assessment was used in the different courses where the Foundry was applied. This multi-level approach encompasses the following elements. Regarding exams, two midterms, with both individual and team work components, were given along with an additional follow-up, redo section for the items that needed additional work from the students. The final was centered on a poster session that was open to the public and displayed all the team-based projects. As shown in Figure 5, a team of experts assessed the projects and based their evaluations on the pedagogical, technical, business, and entrepreneurial aspects of the project. In particular, the level and quality of innovation, patents, Intellectual Property (IP), business plans, pathways to identify
needs, and the proposed solution suggested by the team of students are part of the assessment forum. The formats used have been oral or poster presentations, with the latter being preferred to the former. The panel of judges is provided with a rubric that includes each of the aforementioned assessment areas. The team usually has a captain that is well trained in this type of assessment; the teams of judges gather the data from students, discuss the findings, and come to a consensus to evaluate the team. The final exam contains a portion with questions about all the projects presented in the course. In accordance, it is important to note that the poster session is thus not a competition among teams of students since the focus is on collaborative-based learning and understanding the projects. Consequently, students are encouraged to learn from each other’s contribution and prepare to answer questions in the final assessment of the course. In addition to this poster session, the students are required to submit a summary of their overall work performance as part of the aforementioned Personalized Class Binder of the team.

A recent judge offered the following testimonial regarding this assessment process: I was recently able to witness the outcome of these efforts when I was invited as a member of a cross-curricular team to evaluate the Prototypes for Innovative Technology projects for the CHE 3121, Transfer Sciences II (Fluids) Class. The evaluating team consisted of individuals from health care, business, as well as engineering. The instructor, Dr. Arce, also invited graduate students and K-12 educators. The Chemical Engineering students had to explain their prototype projects (real-world problem, cost analysis, foundational knowledge), and how they used the Renaissance Foundry approach in a way that non-engineers could understand. It was quite a challenge for the students, but they excelled when the faculty member from the College of Business asked about start-up cost, profit margins, and patenting their innovations. The students articulated the societal impacts
of their projects. It was an amazing day of learning for the students and the evaluators. It is remarkable to see in action Chemical Engineering Juniors behaving with all the trademarks of a real Da Vinci-style Professional, several years ahead of something that the National Academy of Engineering envisions happening in 2020!

The overwhelming majority of the comments offered by the judges are that students are clearly mastering the innovation-based principles inherent within the Foundry: they understand the process required to achieve a new prototype that solves or addresses the need identified and they have an excellent understanding of the path to potential commercialization of such innovations. As evidence of this statement, several of these prototypes have been recommended for patent or patent disclosures.

**Exploratory Data Indicating the Effectiveness of the Foundry: Students’ Perspectives**

In addition, qualitative assessments based on students’ perceptions, students’ inputs (via the IDEA evaluations), and debriefing interviews all indicate that the system efficiently produces professionals who display strong characteristics of a new (STEM) Da Vinci-style engineer. During the ChE 3121 course, entitled Transfer Science II (fluids), a qualitative study conducted by Loggins (2012), a graduate student in the Curriculum and Instruction Department, provided valuable data concerning student perceptions related to the role of the *Renaissance* Foundry in their learning. The key points summarizing the students’ input is provided in Table 2.

Another tool utilized for assessing the Foundry was the IDEA evaluation used at TTU where students need to record their answers in a scaled rubric where the upper limit indicates *much higher*. Table 3 shows course evaluation results for a recent offering of the Biotransport (ChE 4661) course previously described in this article. For a class in which the large majority of students (25 of 26) replied to the survey, students scored all four of the instructor-identified learning objectives at the highest level possible (i.e. much higher) when compared to all courses in the IDEA database (third column), all courses that are similar to the Biotransport course and that are in the IDEA database (fourth column), and all courses at TTU (fifth column). These learning objectives relate to innovation and critical thinking, with the high scores indicating a high level of progress towards students becoming expert engineers capable of transferring knowledge.

Moreover, more recent scores continue to reveal a high impact of the approach (Sanders, Mbachu, & Arce, 2015). These student-based inputs are in-line with the comments offered by the panel of judges that assessed the students’ final projects in the different courses. Finally, feedback from employers, both from the co-programs as well as from those hiring graduates for permanent positions, is very encouraging. For example, when they are asked why they are pleased with our students and engineers, they recite back the attributes of the Da Vinci-style engineers!

**Implementation in the TTU Chemical Engineering Curriculum and Impact**

The *Renaissance Foundry* model has been implemented at the Department of Chemical Engineering at TTU systematically and in an increasing manner since 2008. The current

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7 Feedback from the Board of Advisors of the TTU Chemical Engineering Department to Faculty
Table 2

Findings from a Qualitative Study Conducted from Spring 2012-Spring 2013

<table>
<thead>
<tr>
<th>Key Words</th>
<th>Description of Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resources</td>
<td>In the interviews, it was evident that all students took advantage of any and all opportunities to use extra materials (ones suggested by facilitators of learning), interview other professors, form study groups, research books and internet sources, etc., to get the most out of their learning. In this progress, the <em>Resources</em> element of the Foundry plays a critical role (Figure 1).</td>
</tr>
<tr>
<td>Learning Expert</td>
<td>The <em>Renaissance Foundry</em> learning platform promotes student learning by allowing students to take control of their own courses, without relying completely on the teacher. This learning model fosters the development of the <em>Learning Expert</em>, which evolves from the novice level of knowledge that the student initially has at the beginning of the course.</td>
</tr>
<tr>
<td>LES</td>
<td>Hands on will not, by itself, increase students’ understanding of a concept; what is additionally needed is a ‘minds on’ emphasis in the learning of science. This is evidence of the critical role played by the <em>LES</em> in the solution of the <em>Learning Challenge</em> by identifying a suitable <em>Prototype of Innovative Technology</em>.</td>
</tr>
<tr>
<td>Creativity</td>
<td>Learning within this constructivist methodology, such as the <em>Renaissance Foundry</em>, allows instructors to recognize that students have developed a process that promotes creativity in approaching a <em>Learning Challenge</em>. It is clear that the role played by the <em>Prototype of Innovative Technology</em> helps students to identify a need and recognize connections with both the overall society and the fundamentals learned in the course.</td>
</tr>
<tr>
<td>Renaissance Engineer</td>
<td>The <em>Renaissance Foundry</em> promotes creativity in students during their thinking process. In accordance, by being able to apply their experiences from class, and problem solving skills in finding a solution for their <em>Learning Challenge</em>, the Foundry will not only influence their attitudes towards learning, but also better prepare them for the workforce. In short, students acquire essential characteristics of a Renaissance Engineer.</td>
</tr>
</tbody>
</table>

*Notes. The information in this table is modified from Loggins, (2012).*

innovation-driven model – the *Renaissance Foundry* version founded on the elements of Hi PeLE™ started around 2007. Before this version, the platform was focused more on the coach-based applications of Hi-PeLE™ which did not necessarily target the highest level of the Bloom taxonomy (i.e. creativity) as a central focus. Several of the tools outlined in this paper, including the POK, functional-based teams, Learning Cycles, multi-level assessments, and Documentation Cycles, were added and tested before this latter model was identified.

The system has been used also at the Southwestern Indian Polytechnic Institute (Albuquerque, New Mexico) by Pascal and in the K-12 system both in the United States and in Argentina. Prototypes of the Hi-PeLE™ (that led to the *Renaissance Foundry*) have also been tested at several higher level institutions including: the University of Alabama in Huntsville (Huntsville, AL); Mississippi State University (Starkville, MS); The FAMU-FSU College of Engineering (Tallahassee, FL); Rose-Hulman Institute of Technology (Terre Haute, IN); and *La
Table 3

Summary of Adjusted Scores from Evaluation Items deemed as “Essential” Summarized in the IDEA-Based Evaluation of the Biotransport Course

<table>
<thead>
<tr>
<th>IDEA Assessment Item</th>
<th>Progress Score</th>
<th>IDEA Database</th>
<th>IDEA Discipline</th>
<th>TTU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Question 23 – Learning to apply course material (to improve thinking, problem solving, and decisions)</td>
<td>4.9</td>
<td>68 Much Higher</td>
<td>71 Much Higher</td>
<td>68 Much Higher</td>
</tr>
<tr>
<td>Question 24 – Developing specific skills, competencies, and points of view needed by professionals in the field most closely related to this course</td>
<td>4.9</td>
<td>67 Much Higher</td>
<td>70 Much Higher</td>
<td>67 Much Higher</td>
</tr>
<tr>
<td>Question 25 – Acquiring skills in working with others as a member of a team</td>
<td>5.0</td>
<td>66 Much Higher</td>
<td>71 Much Higher</td>
<td>68 Much Higher</td>
</tr>
<tr>
<td>Question 26 – Developing creative capacities (writing, inventing, designing, performing in art, music, drama, etc.)</td>
<td>4.8</td>
<td>63 Much Higher</td>
<td>70 Much Higher</td>
<td>64 Much Higher</td>
</tr>
</tbody>
</table>

*Universidad Nacional del Sur* (Bahia Blanca, Argentina). Courses impacted by the model include ChE 1010 (Introduction to Chemical Engineering), ChE 1510 (Introduction to Computations), ChE 2011 (Chemical and Biological Process Analysis), ChE 3111 (Transfer Science I, Heat Transfer), ChE 3121 (Transfer Science II, Fluids), ChE 4661 (Biotransport), ChE 4131 (Transfer Science III, Mass Transfer), and ChE 4540 (Controls). It is also planned to be incorporated into ChE 4410 (Process Design I) and ChE 4420 (Process Design II) in the upcoming academic years. The implementation follows a systematic strategy to sequentially incorporate all elements of the system. For example, team-based learning and hands-on approaches are introduced as early as ChE 1010 (Introduction to Chemical Engineering) and an intensive training on all aspects of team-based formation, functions, responsibilities, etc., are conducted in ChE 1510 (now ChE 1520 - Introduction to Computations) and ChE 2011 (now ChE 2020 - Chemical and Biological Process Analysis). Other elements of the *LES* and innovation-based learning are discussed and implemented in an increasingly sequential manner in all of the Transfer Science Courses. This way, students develop progressively towards an increasing level of expertise in innovation-driven knowledge that can be adapted to higher level challenges in junior and senior level courses (Tijaro-Rojas, Biernacki, & Arce, 2012).

In conclusion, through the leadership and support of the Chemical Engineering faculty, staff and students, the Department of Chemical Engineering at TTU has undergone a massive transformation during the past decade in an effort to improve student learning and critical thinking to develop and produce Da Vinci-style Engineers. Further, the College of Engineering at TTU has adopted a new model for the graduates of the college—the 21st Century Renaissance Engineers—and plans are in place to extend the implementation of innovation-driven methodologies to the
entire college. In effect, the Renaissance Foundry has already had a substantial impact on the TTU Department of Chemical Engineering and has the potential to completely transform the culture of not only the College of Engineering, but the entire TTU campus and beyond. These broader impacts will be outlined in the following section.

Broader Impacts and Future Directions of the Renaissance Foundry

Effectively, the development of the Hi-PeLE™ has evolved over time. The initial article by Arce and Schreiber (2004) described the basic elements and the general philosophy of the Hi-PeLE™ without any mention of an implementation strategy (IS). After several years of testing different implementation strategies (2004-2007) focused on the mid-range cognitive levels of Bloom’s taxonomy (i.e. application and analysis), the LES was identified to target the highest level in the modified Bloom’s taxonomy (i.e. creativity) (Anderson et al., 2001). The original experimental prototype became the current Prototype for Innovative Technology (Figure 1). As described above, technology here could be a device, an algorithm, a math drill, a new reaction, or any innovation relevant to the Knowledge Acquisition of the course that is being handled. Moreover, the LES is an overall efficient format to implement Knowledge Transfer of the platform.

During this evolutionary time period, which included the transformational years (2003-2007) at the TTU Chemical Engineering department, several other departments across the nation tested this novel approach to teaching engineering students. Professors at Rose-Hulman Institute of Technology, Mississippi State University, University of Alabama at Huntsville, and others contributed to the ongoing development of this teaching and learning model. As previously indicated, the Renaissance Foundry is thus an outcome of the adaptive expertise years (2007-present). The exposure and reception of the platform has been quite promising. For example, Arce in 2009 described a new paradigm change in engineering education towards the NAE 2020 Engineer Model when giving a keynote lecture on the Hi-PeLE™ at an annual meeting of an Engineering Research Center supported by the National Science Foundation (ERC-NSF) (Arce, 2009; Committee of the Engineer of 2020, 2005; NAE, 2005). In consequence, the Foundry was highlighted as one of the best practices in the country to achieve this type of engineer. Further, numerous workshops (co-directed by several of the co-authors of the contribution) at the American Society for Engineering Education-Southeastern Section (ASEE-SE), presentations at selected universities (e.g. Purdue University and the University of New Mexico), and a plenary and an invited panel in Argentina (by the Comparative International Education Society) have assisted in broadening the dissemination of the model to other audiences. This is in addition to a dedicated 2011 session at the ASEE National Meeting in Vancouver, Canada, where several aspects of the model were discussed including one on team development and another one on assessment. Various presentations at the American Institute of Chemical Engineers (AIChE) Annual Meetings

8 The Renaissance Engineering Model Team of the College of Engineering at TTU (Chaired by Associate Dean Darrel Hoy) has recently reported that the Foundry is the only model extensively implemented in a department and that follows the strategic plan of the college (March 2015).
(Education Division), American Society for Engineering Education (ASEE), and the ASEE-SE Annual Meetings have also aided in the dissemination of the model. In 2015, TTU adopted a new Quality Enhancement Program (QEP), and the Foundry played a major role in the design of the new model (Arce et al., 2015). The Renaissance Foundry has also been adapted to drive innovation in academic units (Arce, 2014).

One effort that is currently underway is the partnership between Chemical Engineering and Nursing to develop joint courses and programs at TTU; this is an initiative in which Nursing and Chemical Engineering students would work collaboratively to identify authentic problems from clinical immersions/rotations in the hospital. The nursing students communicate their perspectives to Chemical Engineering students, who do likewise, and ultimately in a Da Vinci-style model, novel solutions would be designed and tested. This unique approach is a win-win effort for both the Nursing and Chemical Engineering students as both groups get the experience of affecting genuine change in their practice settings. This is one of the most effective and unique characteristics of the LES element within the Renaissance Foundry model where students have the opportunity to transfer knowledge (or adapt expertise) to a societal need that, eventually, leads to an innovative technological solution that will impact society. This is an ideal example of a 21st Century Da Vinci (STEM) Professional. Based on this experience as well as the ones described above, the educational model has demonstrated the potential of impacting the entire curriculum of STEM disciplines, including the K-12 population. These observations are solid indications that the Foundry potentially has many places to impact and change the direction of STEM education based on the creativity-driven paradigm.

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9One of the co-authors, Dr. Arce, has tested the model, successfully, in K-12 classes in Argentina and one of his graduate students in Education has applied the model to a STEM Club of 4th graders in a rural elementary school in Crossville, TN
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Conference and Exposition, American Society for Engineering Education, University of Tennessee, Chattanooga, TN.


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