A language-infused approach to introduce Dominican high school students to the logical process of designing experiments to construct knowledge

K-12 Education (Curriculum Integration)

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Abstract: This work reports on the results of a discovery project designed to introduce Dominican high school students to research concepts. The curriculum uses the ubiquitous water rocket to submerge students into the logical process of formulating hypotheses and designing experiments to construct knowledge. The curriculum is intended to help students understand how and why engineers and scientists build knowledge. It makes research methods less abstract to the students and helps them learn to draw the connection between hypothesis formulation and well-designed experiments that build knowledge. The activities encourage students (a) to explore their mental models for hypothesis testing, research, and experimentation, (b) to refine their models and to investigate connections among related concepts, (c) to apply experiment design concepts and principles in order to create experiments and to reason about hypothesis-testing without recourse to the manipulation of equations, (d) to develop problem-solving skills anchored in an understanding of fundamental concepts and principles, and (e) to use language and technology tools to communicate discoveries in a clear and meaningful manner. Our goal is to enable students to obtain a deeper understanding of the meaning of research, design and analysis of experiments (DAE), and hypothesis testing concepts, and to provide them with a greater facility for applying these concepts to problem-solving - or at the very least, to point them in the right direction. Turning pre-college students into researchers is a way to motivate the deep learning of facts, creativity, and the development of knowledge-building skills that students will need to be successful in college and in their daily lives.

Despite limited skills and other barriers, the students involved in this program were able to grasp complex DAE concepts and produced simple but well-designed experiments. This pilot provided valuable insights to ways in which to improve the curriculum design. A new test will be conducted in summer 2011. We believe this curriculum will be useful to educators. It deals explicitly with the subject of designing effective experiments.

Keywords: Experimentation, Language-Infused, Design of Experiments, Engineering Education, Engagement, High School

Introduction

Experimentation is a typical element in science and technology activities intended for pre-college students, but principles of the design and analysis of experiments (DAE) are rarely
A language-infused approach to introduce Dominican high school students to the logical process of designing experiments to construct knowledge
dealt with explicitly in these activities. This work reports on the results of a discovery project designed to introduce high school students from the Itabo-Nigua region of the Dominican Republic to research concepts. The DAE curriculum project focuses specifically on the process of constructing well-designed experiments. It was piloted in the summer of 2009 for four weeks and a total of 36 hours. We used bottle rockets to submerge students into the logical process of formulating hypotheses or research questions and translating them into well-designed experiments to construct knowledge or discover facts. The main goal was to help the students experience how and why engineers and scientists build knowledge. First, we gave students the opportunity to experience science and technology by developing an understanding of such concepts as inertia, air resistance, Newton’s laws, acceleration, projectile motion, gravity, measurement, and friction. Second, we helped students to gain a better handle on necessary mathematics and statistical fundamentals, as well as to improve their understanding of problem-solving and the engineering design cycle. Third, students were driven into DAE, which helped them internalize fundamental principles and concepts through activities that engaged them in the continuous exploration and improvement of their mental models. We used NASA and Lego Education bottle rocket curricula resources to structure their introduction to basic rocket science.

The DAE curriculum project follows a language-infused STEM (Science, Technology, Engineering and Mathematics) – STEM-L - curriculum approach in order to promote deeper learning, steering students away from memorization and towards the internalization of concepts and ideas. The language-infused DAE curriculum project focuses on the process (the learning environment or classroom) and engages the students actively in building their own understanding and knowledge. The students are the main agents in the process of discovery and learning. They are immersed in the process of exploring and refining their mental models about rocket science, research, and experimentation. Peer-assistance and team work are integral components of the strategy. Working in small teams, students in the DAE curriculum project analyzed problem situations and answered questions, shared ideas and reflected on their views or perceptions, explored the meaning of complex concepts through inquiry and hands-on activities, and improved their understanding of experimentation and knowledge-building. Students were driven to strive further in their learning inquiries, helping them to explore weaknesses in their own understanding and knowledge; to think critically, considering the meaning of words and concepts carefully, pondering the logic of ideas; to develop arguments; and to reason.

The language-infused DAE curriculum approach requires less lecturing by the teacher, but it is time-demanding and requires flexibility for adjusting activities to the students’ needs. The next section explains more about the language-infused STEM curricular approach.

Why rocket science? Rocket science has been an exciting field of discovery for thousands of years. It holds enormous importance for humanity in the twenty-first century, as the exploration of space for commercial and research purposes continues to expand, Renewed efforts to return to the moon and ongoing explorations of Mars for human landing in the near future are challenging scientists and engineers to design new generations of rockets to advance these initiatives and improve our knowledge of the galaxy. Bottle rockets are
A language-infused approach to introduce Dominican high school students to the logical process of designing experiments to construct knowledge

excellent tools for introducing students to the exciting field of rocket science. They have been used extensively in formal and informal classroom settings in the USA, but we are not aware of similar efforts in Dominican classrooms. Rocket science does not appear to be an element of high school science curricula in the Dominican Republic (DR). Newton’s laws are treated in a limited way in some science textbooks intended for high school, but the students involved in the pilot program were unfamiliar with the laws. Furthermore, public and private K-12 schools in the DR do not integrate engineering and technology curricula. MACILE, which stands for “Mathematics, Science, Engineering, and Language” in Spanish, is the first program to introduce engineering and technology education in K-12 classrooms in the country. Thus, using bottle rockets for this project allow us to expose Dominican teachers and students to a very exciting science and technology field and to challenge the students’ imagination. They learned how bottle rockets can offer magnificent opportunities for extending learning in mathematics, the sciences, technology and engineering. In addition, we believed bottle rocket activities were great instruments for introducing students to DAE and to the challenge of producing well-designed experiments. We expected the students to be motivated to experiment and learn. And, this was in fact the case; the students enjoyed learning about rocket science and had no major difficulties with the curriculum. They demonstrated creative abilities and gained good understanding of many concepts such as inertia, gravity, air resistance, Newton’s laws, acceleration, projectile motion, work and energy or impulse and momentum, measurements, basic trigonometry, and the estimation of altitude.

Why design and analysis of experiments (DAE)? DAE is essential for the design of robust processes, products, and systems. Introducing pre-college students to basic concepts of DAE and hypothesis-testing is a way to motivate deep learning, creativity, and the development of analytical skills that students will need to be successful in college. It is also an effective way to introduce them to research. Despite limitations in their skills and in other areas, the Dominican students involved in our program internalized complex DAE concepts and produced simple but well-designed experiments. They demonstrated more sophisticated mental models about research and better analytical skills by the end of the summer, and their language skills improved, as well.

The pilot provided valuable insights for future improvement. We believe this curriculum will be useful to educators interested in engineering and technology education, but the method can also be useful for science educators. In the following section we explain the foundation and origins for the STEM-L approach. After that we explain the processes we used to introduce students to basic rocket science and to the design and analysis of experiments (DAE). The steps for guiding students through the process of producing a well-designed experiment are illustrated next using a case example. Finally, we present concluding remarks, challenges, and suggestions for the future.

A language-infused STEM curricular activity: foundation
Science and engineering activities often include a language component such as requiring written reports or oral presentations. A language-infused STEM (Science, Technology, Engineering, and Mathematics) – STEM-L - curricular activity may includes these components, but its main focus is to drive students to go beyond in their learning inquiries,
helping them to explore weaknesses and fuzzy areas in their own understanding and knowledge; to think critically, considering the meaning of words and concepts carefully, pondering the truth of concepts and the logic of ideas; to develop arguments; and to reason. A STEM-L curriculum promotes deeper learning, steering students away from memorization and driving them towards the internalization of concepts and ideas. Our approach is anchored in basic principles of fuzziness, complexity, and system dynamics. Fuzziness is the opposite of precision. It is inherent in our perception of reality and in every kind of activity based on this perception, such as thinking and speaking, learning and understanding, knowledge, creating, and making sense of events in life (Dimitrov, 2002). Individual perceptions of reality define the mental models controlling our decisions. All decisions are made on the basis of these mental models (Forrester, 1997). These models are rich, contain tremendous stores of information, and are often sufficiently accurate about parts of a system or field of knowledge. They are fuzzy in nature, incomplete, or limited in their capacity. It follows that the students’ mental models, their understanding and knowing, and their experience of life govern their decisions about learning. Students bring these models into the classrooms and their capacities constrain how well the students can perform. It is necessary, therefore, that the classroom process be designed to guide students to explore, refine, or enrich these models in order to motivate deeper learning. This process will unfold as students realize their understanding and knowledge are important, discover the fuzziness in their own thinking, and gain confidence in their abilities to discover and learn. For example, eliciting the students’ perceptions of research was essential for facilitating their improvement. Their views were narrow; they emerged from their experiences with school projects, which did not encourage deeper thinking.

Students demonstrated an initial belief in the idea that “if it was written in a book it must be true.” Research, to them, was equivalent to finding a source of information – a book, the Internet – and reproducing (copying) from it everything that was found about the assigned topic. Research quality was synonymous with quantity because their education system rewards the latter: “I always get good grades in my projects because I copy a lot,” as one student said. Other students expressed similar view. By immersing students in the process of questioning their own understanding and beliefs about research and of designing experiments to verify or refute their research questions, the students’ views about research grew more sophisticated: they were exposed to a different experience, and their reasoning and analytical skills improved over time.

The essence of the STEM-L curriculum revolves around creating learning environments that motivate students engage themselves continuously in learning and discovering. [This internalizes three fundamental truths: (1) human understanding and knowing have their own dynamics, and students’ mental models are driven by these dynamics; they are evolving pictures and the ways in which they evolve are important. (2) Human understanding and knowing grow from within the individual; knowledge-building can be guided and motivated, but it cannot be implanted or impose from outside. (3) Fuzziness and unreliability can never be fully eliminated from the human perception of reality, from our thinking and understanding, and from our experience of life; consequently, these elements cannot be completely eliminated from the human learning process. Considered
A language-infused approach to introduce Dominican high school students to the logical process of designing experiments to construct knowledge

together, these fundamental truths clearly show that for sustainable advancement in learning, the process of exploring and refining students’ mental models must be continuous. And, this requires robust [challenging and motivating] learning environments or processes; environments that motivate, not discourage, knowledge-building. Research has shown that the most significant component in the quality of a learning environment is the implementation of the curriculum (Schommer, 1990, 1993; Yager, 1995; Cohan, 1994; Howard et al., 2000). That is, the curriculum in itself is insufficient to ensure a high level of learning. The implementation process is the key to determining such success. Thus, in a STEM-L curriculum, the teacher’s role is to ignite the students’ desire to discover and to learn. The ultimate goal of a language-infused curriculum should be to develop learning environments - processes or classrooms – that do not impede the inner drive for wisdom [knowledge], but rather encourage its outward fulfillment. These are robust processes where students’ mental models are challenge continuously. This view has been advocated by ancient (i.e, Socrates) and modern (i.e., Einstein) thinkers and is supported by extensive research findings in cognitive science and education. Rich examples can be found in the new science of learning literature compiled in the Cambridge Handbook of the Learning Sciences, edited by R. K. Sawyer (Sawyer, 2005) and in the NRC Report *How People Learn*, first published in 1999 and with an expanded edition published in 2000 (Bransford, Brown & Cocking, 2000), as well as in other sources like Egan (1989, 1992, 1998), Dimitrov (2002) and Forrester (1997). A STEM-L curriculum focuses on the process (the learning environment or classroom), providing an approach that engages students actively in building their understanding and knowing and retains the teacher’s role as a guide.

The exercises and activities performed during the DAE curriculum project were designed to meet the needs and requirements of students in order to improve their learning and motivate their creativity. Students were encouraged to articulate and ponder their beliefs and understanding and to dig deeper to discover truths and misconceptions. This process required considerable adjustments from the students and a great deal of time in order to provide them with the attention they needed. Their skill levels were far below those expected for their grade levels. The students had to adjust to take more control of their process of discovering and learning, which led to some frustrating moments, as well as many enjoyable ones. Good results emerged over time as the students gained more confidence in their abilities. With the inquiry-based activities and class discussions, the students discovered that their perceptions were often limited, or fuzzy. They tried to improve their thinking and, in the process, they internalized some complex DAE concepts fairly well, developed a more sophisticated view of research, presented well-formulated questions or hypotheses, and produced simple, well-designed experiments. Improvement in their language skills – writing, reading, and verbal – emerged naturally and gradually from their engagement in the exercises.

In most curricula, assessments typically focus on measuring skills. In a STEM-L curriculum the fuzziness of the students’ mental models and their experiences, must also be considered in the evaluations, since skills improvement and the students’ perceptions of learning during the course are likely to differ. For example, at the end of the project an evaluation of the students’ math skills and their internalization of basic DAE and rocketry
principles still showed uncertainty or fuzziness; the students, however, perceived that they had learned a lot about rockets, mathematics, DAE, and research during the period. And in fact they did. Their perceptions of what they learned reflected their experience. This project was packed with novelties – rockets, experimentation, peer-assistance, exciting science, and probing their own thinking. The students learned a lot about these new areas and this knowledge will play a role in shaping their future learning. Assessments that ignore the students’ perceptions of learning are less likely to motivate learning, and may even discourage it.

Finally, it should be borne in mind that a language-infused STEM curriculum requires a great deal of flexibility from the teachers. For us it was necessary to anticipate possible scenarios that could emerge and prepare to provide adequate support to the students. This type of support is often time-intensive. It requires the patience to resist the impulse to inject answers when students’ views differ from what is expected. It also requires a great deal of confidence with the content of the curriculum and the knowledge domain.

The origin of a language-infused STEM curricular approach

The idea for the STEM-L curricular approach germinated from observations that took place during the MACILE pilot program in summer 2007 and 2008. MACILE is a COSOLA²-sponsored program that aims to advance engineering education in pre-college classrooms in less advantaged communities.

MACILE has operated in the Itabo-Nigua (Ytabo) region of the Dominican Republic since 2007. It is the first pre-college engineering education program in the country (Vargas, 2009, Shumway et al., 2010). During the pilot we observed:

- First, high school students possess a fairly extensive technical-scientific vocabulary, but they often use words or concepts without having properly understood their meanings, or having only partially understood them.

- Second, the students’ perceptions about how much they learned in the MACILE program and the skills they showed in the assessments were incongruent. They claimed they learned a lot in mathematics, science, and Spanish, but while their abilities did improve during the periods, the gains were not remarkable. In mathematics, for example, despite a claim by students that they liked mathematics and the excellent grades they achieved in school, students selected to participate in MACILE showed skill levels that were far below those expected for their grade levels. At the end of the summer program, the students demonstrated modest improvements in math skills and stronger awareness of related concepts. However, when they assessed their learning, 100% of the students indicated that they learned a lot. At the same time, they also recognized their difficulties with mathematics. Similar results were observed with Spanish and science and technology assessments. These findings indicate to us that students were actively assessing their experiences with MACILE and that their experiences were important to them.

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A language-infused approach to introduce Dominican high school students to the logical process of designing experiments to construct knowledge

They found the MACILE learning environment and the activities motivating and challenging.

- Third, we were challenged to design a Spanish curriculum that could motivate talented young people to want to learn the language and that could inspire them to be creative. The initial model for the STEM program did not contemplate a language component. It was added later out of necessity. During the 2007 pilot we realized the students’ language skills were extremely poor. Some were nearing high school graduation unable to write their own names properly and unable to articulate their ideas coherently in writing or verbally; none could produce a simple paragraph dictated to them without several errors (Vargas, 2009). We understood that the problem needed to be addressed and that it required a nontraditional curricular approach. We decided on a model that emphasizes analytical thinking and creativity while discouraging memorization; incorporates team work and peer-assistance; and integrates a contextual framework relevant to the students’ own lives. Dominican history, culture, and literature form the foundation of the curriculum. Grammatical structures, orthographical rules and other language principles are woven into the lessons and activities without being their main objects. They derive naturally from the readings and discussions of the underlying topics.

The results for the first year of implementation of the MACILE Spanish program exceeded expectations and have been good each year since then. The teachers’ and students’ language skills improved, in some cases remarkably. But more significant was their perception of the program. They found it unique, challenging, and helpful (see Vargas, 2009). In the classrooms, the students transformed from passive to fully engaged, active, and creative learners and from poor readers and writers to better ones after a relatively short period. In the classrooms, students were motivated to articulate their own mental models, assess their misconceptions, and evaluate their skills. They learned to recognize strengths and weaknesses, assisting each other through constructive criticism. They internalized nuances and structures of language as they learned about their history and culture. Some discovered a passion for writing and wrote poems and short stories, while others found opportunities to display their artistic and creative skills, producing a historical drama and pictorial recreations of locations, historical events, and indigenous villages. Teachers taking the workshops discovered their limitations as well. Some recognized their own reading and writing skills were lacking and that their understanding of Dominican history and literature required improvement (Vargas, 2009).

These experiences planted the seeds from which the idea of infusing language into mathematics, science, and engineering curricular activities in order to promote deep learning began to spring. This idea seemed natural, considering the fundamental role of language in any human learning activity and the interrelationships among the fields of learning. The anchoring for our STEM-L approach, however, is found in the principles of fuzziness, complexity, and system dynamics. As discussed earlier, human understanding and knowledge are inherently fuzzy. Learning grows from within the individual and its development is dynamic, imperfect, and uncertain. Individuals base decisions on their
A language-infused approach to introduce Dominican high school students to the logical process of designing experiments to construct knowledge

mental models – that is, on perceptions of reality, knowledge and understanding. Thus, the design of robust learning environments – processes that internalize complexities - is necessary to challenge the students’ imagination and motivate deep learning. This view is also supported by extensive research findings from cognitive science and education (Egan (1989, 1992, 1998; Sawyer, 2005; Bransford, Brown & Cocking, 2000). In the following section we report on the implementation process and results for our pilot.

Basic rocket science with bottle rockets
In the DAE curriculum project we used bottle rockets to submerge high school students into the logical process of formulating hypotheses or research questions and translating them into well-designed experiments that could construct knowledge. Four main reasons for selecting bottle rockets as the main activity for this project include: (1) Rocket science is an exciting field that holds tremendous importance for humankind in the 21st century, as the exploration of space for commercial, research, and national security purposes continues to advance. (2) Introducing talented young people to rocket science in an exciting way can fire up their imagination and desire to learn. (3) Bottle rockets offer inexpensive, magnificent opportunities for extending learning in mathematics, the sciences, technology, and engineering. (4) Rocket science was a novelty for Dominican teachers and students, so we expected the students to be more motivated to learn and experiment.

First, we led the students to experience science and technology and develop an understanding of such concepts as inertia, air resistance, Newton’s laws, acceleration, projectable motion, gravity, measurement, and friction. Second, we helped the students gain a better handle on necessary mathematics and statistic fundamentals, as well as an improved understanding of problem-solving and the engineering design cycle. Students practiced controlling variables, observing behavior or results, collecting and analyzing data, and interpreting results. Third, we introduced the students to basic principles of design and analysis of experiments (DAE), guiding them through the logical process of translating their research hypotheses or questions into well-designed experiments to build knowledge or discover facts. We used NASA and Lego Education bottle rocket curricula to structure the introduction. Very little specialized equipment was required. The launcher and the computer were the most specialized equipment. The materials were recyclable or easily available.

The DAE curriculum project engages students in conceptual reasoning at a much deeper level than is normally the case in Dominican classrooms and science and technology activities of this nature. It follows a language-infused approach, immersing the students in the process of exploring and refining their mental models to promote deeper learning about research, basic rocket science, and experimentation. The action-oriented activities are challenging and engaging; they are intended to curb the students’ natural tendency to learn by rote and through the manipulation of formulas. As a result, students require less lecturing by the teacher and a more active engagement in the process or learning. Working in teams, students use concepts to analyze problem situations and search for answers to questions; they explore the meaning of concepts and words through inquiry and hands-on
activities and share their perceptions or ideas. Students are the main agents in the process of learning; Dominican students have adjusted well to the challenge.

The introduction to basic rocket science began with an exercise designed to explore what students already knew (their mental models) about rockets, Newton’s laws, NASA, and general aeronautics. Following that activity, students read and pondered a prepared article based on materials from NASA (Rockets: An Educator’s Guide with Activities in Mathematics, Science, and Technology) and other sources. The reading was followed by hands-on activities designed to help the students internalize the scientific principles in Newton’s laws of motion, as well as basic rocket science concepts. After completing the activities, students documented their understanding of key concepts, noticing any variation from their initial perceptions of the concepts. Next, each team built a bottle rocket and practiced launching it. The teams used the same rocket design, materials, and specifications (Lego Education kit). Each rocket was launched with and without water, and the students recorded their observations, taking only visual estimates of the altitude reached by rockets in flight. They discussed their observations in class and suggested methods for improving the accuracy of their measurements. Since there was no mechanical altimeter available, students suggested fly time as a better estimate, with a longer time implying a higher altitude. After reading about the Altitude Tracking Device (ATD), they also considered this option for estimating the altitude reached by their rockets. They built the ATDs and practiced using the devices. The teams also used a stopwatch to estimate the rockets’ flight time. These exercises were followed with a series of activities focusing on a review of fundamental mathematic and statistical concepts, and problem-solving. The engineering design cycle was used as the foundation for improving problem solving abilities.

Following the introduction to basic rocket science, students engaged in a research questions development exercise and explored their understanding of research, in order to begin steering their minds into DAE.

**Preparing the students’ minds for design and analysis of experiments (DAE)**

The process of introducing students to the concepts and principles of DAE began with a research questions development exercise (RQDE) in which the students developed research questions or hypotheses about things they wanted to research about rockets and proposed experimental plans for discovering facts or improving their understanding. These questions or ideas were discussed within the teams. At the end, each team selected the questions or hypotheses they would research and elaborated an experimentation plan to verify or refute the questions. The teams recorded their proposals in logs, shared their proposals with the class to further their discussion, and submitted copies for review and feedback. Over time, these proposals evolved into the students’ final research proposals (see below).

The next exercise, aimed at digging deeper into the beliefs and knowledge, engaged the students into exploring and refining their understanding of research, experimentation, hypothesis-testing, theory, and facts. This exercise invited the teams to reflect about
specific questions and to draw logical connections among concepts. Each team recorded its formed theories or views in the team log and shared them with the class. [Note: logs and other works are returned to the students at the end of each summer program.] In the next step students read a brief article about research, compiled from various sources. This included topics such as types of research – experimental and non-experimental – and methods used for conducting research. It explained the importance and limitations of experiments, including issues related to experiment design and the validity of results. In addition to the reading, students were encouraged to consult the dictionary, encyclopedias, and other available resources to consider and compare the information from these sources and to draw their own conclusions about research, experimentation, and facts. [The Internet was not considered for this exercise due to accessibility, but some students found ways to access the Internet.] The teams could review their prior views, but they had to elaborate their responses, showing what they understood and explaining why they were modifying their views. That is, they could not copy verbatim from the sources. This exercise was time-intensive and difficult, mainly because the students lacked experience with this kind of activity and because of language skill limitations. Consequently, multiple rewrites were necessary.

These exercises allowed the students to assess their understanding of research and broaden their views. They also provided an opportunity to review proper quotation and citation of sources, two important elements in research. The students’ initial perceptions of research were narrow. Research, for them, consisted of finding one or more sources about an assigned topic and then lifting [copying] verbatim everything, or as much information as possible, from each source. This notion was grounded in the students’ experience and beliefs. If written, it was a fact to them; questioning the validity of the information in a text or forming a critical opinion about it was not associated with research, and they had not been challenged to think otherwise. The students had been encouraged to equate quality of research with the quantity of information copied and expressed some of the following ideas: “The teacher likes when you write a lot;” “I always get good grades because I copy a lot;” and “I copy until my wrist hurts.” The concepts of quoting a source, citing it, and copyrights were essentially new to them. The bibliography indicated where the information copied came from; why were citing or quoting necessary? How was it done? Unfortunately, time did not permit us to give adequate attention to these areas and improvement will be needed on them in the future.

In general, RQDE and the mental model assessment exercises were a good experience that motivated deeper thinking and creativity. The students grew more aware of their thinking and developed more confidence in their abilities to detect uncertainty. They reflected on their curiosity and planned experimentation strategies to discover answers to questions or further explore theories. Importantly, they were more able to relate research to facts after completing the exercises. A main goal of the DAE curriculum project was to help the students understand how and why engineers and scientists build knowledge. Thus, how well they understood the relationship between knowledge-building, research, and experimentation was important. The exercises also encouraged the students to grow more comfortable with an approach that challenges their natural tendency to learn by rote, to engage in mere repetition, and to accept information as fact. They were engaged agents in
A language-infused approach to introduce Dominican high school students to the logical process of designing experiments to construct knowledge

an active search for knowledge and facts, building on what they knew and thinking critically. Through their teamwork, they analyzed problem situations and answered questions; explored the meaning of concepts through inquiry and hands-on activities; and shared their theories or ideas, reflecting on them. We guided the learning process, but in most instances, the students had to clarify their own ideas.

At the end, the teams reviewed their initial research proposals and made changes or modifications to them. In the next section we describe the approach taken to guide students through the process of producing well-designed experiments, using a team proposal as a case. The activities chosen to introduce the students to basic DAE principles responded to needs revealed in the students’ own proposals.

The experiment design process
This and the following section report steps and activities structured to engage students directly in the process of designing experiments, starting from research proposals (definition of the hypotheses or research questions) to choice of experimental designs, performing the experiments, and making sense of results. The students worked on many questions and reviewed relevant concepts during the activities. The level of detail was kept manageable, focusing primarily on those basic concepts and principles of DAE that were relevant and would help the students design the types of experiments proposed.

Through the activities, the students became fully immersed in internalizing the basic concepts and principles of DAE while designing experiments. We started with an exercise about processes and systems, emphasizing how experiments are used to design and study the performance of processes and systems. A goal was for the students to be able to define a system and recognize simple and complicated ones, to represent a process, and to realize that systems and processes are ubiquitous in life. Another goal was to familiarize the students with the engineering design cycle (EDC) - ask, imagine, plan, create, and improve –drawing connection between the EDC steps and the strategy for producing well-designed experiments, as described in Montgomery (2005):

1. Ask → Define the problem; develop all ideas about the objectives of the experiments; consult with experts or those with knowledge of the problem; consider the constraints
2. Imagine → Conduct pre-experimental planning: formulate possible research questions or hypotheses; define possible variables or factors and the constraints; consider the requirements (materials, equipment, time, skill requirements, resources)
3. Planning → Select the appropriate experiment and formalize the final plan for conducting the experiment; verify that the experiment selected addresses the research question, hypothesis, or problem; ensure all requirements are satisfied
4. Create → Perform the experiment
5. Improve → Perform analysis of the data; derive conclusions and make recommendations

Some efforts were made to improve students’ understanding of the relationships between research questions or hypotheses, the identification and classification of factors or
A language-infused approach to introduce Dominican high school students to the logical process of designing experiments to construct knowledge

variables, the selection of appropriate experiments, and the production of appropriate experimental plans. Since the primary goal was to help students produce simple, but well-designed, experiments, it was important that they also understood these important facts about experiments: (1) the results of an experiment depend on the hypothesis being tested. (2) Experiments are limited. They provide only partial pictures of the processes, systems, or products evaluated. Not all variables or aspects of a process, system, or product can be tested within a single experiment. (3) The accuracy of the results depends on the design of the experiment and how the data are analyzed; a poor design produces poor results, which can lead to poor decisions. (4) Experiments are essential for continuous improvement and advancement in science and technology. Some of the concepts reviewed and why we chose to focus on them are considered next.

**Characterization vs. optimization experiments:** The objective of the activity was to help students differentiate between the questions or hypotheses typically answered by these types of experiments and when they are normally performed, then define their type of experiment. The students evaluated their research questions with respect to the references R1 and R2 to characterize the types of research they were performing.

- **R1.** Characterization experiments: Which factors (both controllable and uncontrollable) affect the altitude the rocket can achieve?
- **R2.** Optimization experiments: Which level of a factor (controllable and uncontrollable) will maximize the altitude that the rocket can achieve?

**Prototype vs. simulation in product design experiment:** The students designed and built prototypes of their bottle rockets to perform the proposed experiments and select the best design. Thus, it was important for them to explore and refine their understanding of prototypes and simulation models. By realizing the differences between these types of experiments, their capacities and limitations, the students gained awareness of critical issues influencing the decision about these experiments such as cost, risks, time, human expertise, and moral hazards associated with them. For example, students appreciated learning why astronauts experience living in zero gravity conditions and manage their spacecraft in simulated environments that replicate the real ones, long before they are lifted into space. The students learned about requirements for designing and building prototypes and simulation models. They discovered that simulation models are helpful learning tools. The students manipulated and controlled many variables, saw their hypotheses verified or refuted, and viewed results graphically. We used freely available water rocket simulators (Water Rocket Fun v3.4 from Software for Fun and Education; RocketModeller II Simulator by Steve Guitierrez, available at NASA.gov), but faced difficulties with Internet access, English language barriers, and the reliability of the electric power. These limited the introduction to simulation.

**Mixture experiment:** Some teams were testing the effects of different rocket fuels on the altitude a bottle rocket could achieve. They proposed to formulate mixtures of several ingredients, such as regular tap water, soda, and shampoo. Therefore, learning about mixture experiments was relevant. We used two simple, instructive, and fun activities to demonstrate chemical mixture principles: formulating vinaigrettes and producing colors.
Performing the activities helped the students gain some understanding of proportions and of some of the characteristics of chemical mixtures. They were also fun learning experience in other respects. For example, the students enjoyed learning that vinaigrette, a Dominican staple, is a chemical product. A review of relevant algebra concepts was also required. At the end, as we show below, the exercises helped the students think deeper about the compositions of their mixtures and the various factors – controllable, fixed, and uncontrollable – that impacted the validity of their experiment designs. They made improvements to their proposed experiments, accordingly, such as specifying the proportions for the mixes, differentiating the factors or variables considered, and specifying factors not previously considered in the proposals, such as the temperature of the mixture, volume, proportions, pressure units (psi), ambience temperature, and the rocket design.

**Randomization, replication, and repeated measurements:** Because these are fundamental components of a well-designed experiment, it was important to ensure that students learned about these concepts. First we elicited what they already knew about these concepts. In general, their views were fuzzy, but they had the most difficulties with the concept of randomness. This was due, in part, to their limited understanding of probability and statistics. For example, for the students the act, rather than the outcome, of rolling a dice was random. They believed the grades students would get on a test were not random, because if they studied hard they could get good grades. That is, in their view, the student could control the outcome of the test, which makes sense. The height of ocean waves crashing on the beach every five minutes was not random to them. Their handling of replication and repeated measurements was better than their handling of randomness, but they had difficulty drawing connections between replication, repeated measurements and abstract concepts like reliability, variation, and errors. The students performed two simple activities to gain hands-on practice with randomization: the magic hat and dice and balls. The magic hat activity involved allocating students to various teams in a random order. The dice and balls activity involved determining the order in which six balls, marked 1 through 6, could be dropped in a basket. The objectives of the two activities were to help the students differentiate between different random events and to provide them with tools they could apply to randomizing their own experiments. Afterward, the students still showed difficulties understanding that rolling the dice or picking a name from the hat were not random events, whereas the outcomes - the numbers and names that resulted from such activities - were indeed random. There was confusion when using similar approaches as in these activities to try to randomize the experimental runs.

Replication and repeated measurements and their relationship to the applicability of the experimental results became clearer after the students gained some experience. The measurement exercise consisted of launching the bottle rockets and taking measurements of the angle formed by the rockets in flight, then using these measurements to estimate the altitude. For each launch, two measuring teams were positioned in two tracking stations with a baseline of approximately 11 meters (25 ft). Each measuring team used the Altitude Tracker Device to approximate the angle and height of the rocket’s flight. The average of the two angles (one for each measuring team) was also computed for each launch, and this was used to estimate the altitude. That is, three estimates of the altitude were computed for
A language-infused approach to introduce Dominican high school students to the logical process of designing experiments to construct knowledge

each launch. In addition, each team estimated the rocket flight time using a stopwatch. There were four (4) launches in total with no replications, eight (8) measurements of the projectile angle, four (4) estimate of the average angle, and four (4) measurements of the flight time. The rocket design was the same for each rocket used (four in total); they used the same volume of water (10oz), the same temperature (cold, from the tap), and the same pressure in psi (90). The students noticed variations in the measurements taken by measuring teams for each launch. These varied both between launches and within launches. As a result, estimates of the altitudes reached by the rockets – using both the individual and average observations - varied as well. The students compared the single altitude measurement estimates with respect to the altitude estimate computed using the average angle and recorded the deviations. These observations provided the students with concrete information to help them understand better the concepts of variability and error. This practice exercise was also helpful in that it allowed the students to appreciate the possibility of human error and to realize that the “human factor” must be accounted for in any experiment. At the conclusion of the exercise, the students discussed several questions intended to help them assess their reasoning about the validity of the results. Two examples are: (1) Can results from an experiment be accepted as truth if variations and errors are possible? (2) What can you do to improve the usability of the results?

Diving into the experiment design process
This section highlights the approach followed to guide students through the process of designing experiments. The process developed around the teams’ proposals. Here, we present the case of team Rocket Power’s proposal, showing how their experiment designs evolved over time. All the proposals, however, were analyzed and discussed in class. There were four teams: Rocket Power, Esmal, Dominican NASA, and BM^2G. The teams were comprised of three or three high school students. The students had attended the MACILE summer program in the prior year. Each team submitted an initial proposal that stated the hypotheses or questions they wished to research and a plan for conducting the experiment. Each proposal had to include initial designs for rocket prototypes, along with corresponding specifications, information about the materials that would be used, and perceived constraints in the experiment. The proposals acted as points of reference for the activities chosen to help the students gain a deeper understanding of basic DAE principles and building better-designed experiments. These activities were intended to engage students in the process of improving their understanding, and eliciting their theories and possible misconceptions. Some of the activities were explained in the preceding section. Table XX below captures the evolution of team Rocket Power’s proposal. [Note: the translations from Spanish into English are kept as faithful as possible to the original version.]

Rocket Power’s proposal included two questions or hypotheses:

RQ1: Will soda produce more pressure than water?
RD2: The size of the fins combined with using the soda as fuel will produce a higher impulse in less time.

The team proposed to build two prototypes – “one with big fins and soda for fuel and the other with small fins and water; then we will exchange the fuel” – to test RQ1 and RQ2.
They also provided two rocket designs, one for each proposed prototype, as well as two different fin designs, one labeled “big” and the other “small.” The designs included no specifications about dimensions or materials.

We began working with this team by addressing four problem areas identified in the proposal: (1) the clarity of questions or hypotheses; (2) incomplete experimental plan; (3) lack of specifications for the rocket and fin designs; and (4) incomplete consideration of the experimental factors. The identification, classification, and selection of factors – design or controllable, fixed, and noncontrollable - was considered first. We began with a simple exercise where the students tried to identify all the factors or variables defining or controlling the rocket as a system, as well as those determining its stability in flight and the altitude it could reach. These factors were then classified into the various types, first using an example question and then considering the team’s proposal. Rocket Power identified two design factors in their experiment, each with two levels: rocket fuel (soda and water) and the size of the fin (small and large). Through further discussion, they recognized their errors with respect to these factors. For example, the correct levels for fuel were: soda plus water and water.

The next exercise addressed the issue of clarity of the research questions or hypotheses in relation to the proposed prototypes and experimental plans. The goal was to help students distinguish ambiguous from specific terms or assertions and to determine whether or not the correspondence between the hypotheses and proposed experiment was logical. Several problems were evident with Rocket Power’s proposal in this regard: (1) In hypothesis RD2, fin size is identified as the design factor to be controlled, but the proposed rocket prototype and fin designs showed the fin design as the design factor, rather than the size. Rocket Power submitted two different designs for the fins. (2) The fin dimensions were not specified in the designs. (3) The ambiguous terms - “small” and “big” – were stated as the fin size levels without adding further clarification. After performing some simple exercises comparing some figures in term of their dimensions, volumes, and geometrical shapes, students better understood conceptual differences, why terms such as “small” and “big” were ambiguous, and why it was necessary to be specific about dimensions, volumes, proportions, geometric shape, and other characteristics of the design. They were also better able to distinguish fixed from variable factors. Rocket Power specified fin design as the design factor, composed of two levels. The final drawing for the fins specified only some of the dimensions (Figure 1).

Two additional factors interfering with the clarity of the hypotheses were limited experience and language skills. The students had no prior experience with experimentation or the formulation of research hypotheses. They needed time to build confidence. Rocket Power was able to improve the hypotheses RQ1 and RQ2 as the team improved their conceptual understanding, though some confusion remained (Table A1), as evidenced by the students’ revised hypotheses/questions (H1 and H2):

\[ H1 \text{ (RQ2): The fin design affects the stability of the rocket in flight.} \]
\[ H2 \text{ (RQ1): A fuel mixture with less density and higher volume will produce a greater impulse in less time.} \]
In H2, the phrases “less density” and “higher volume” are referring to levels of the factor fuel mixture and are still ambiguous. But the team had also specified two levels – warm water and warm water plus soda - for the design factor fuel mixture (Table A1); thus, it was necessary for the team to clarify the levels. After explaining their rationale, it was clear that the students used an underlying reasoning that was logical. With the term “less density,” Rocket Power was referencing the proportions of warm water and soda in the mixture. They believed that more soda increased the density of the mixture and wanted to use a mixture with a higher proportion of water and less soda. With the term, “higher volume,” the team referred to a specific volume. Their observations from simulated experiments and actual launching led the members of Rocket Power to believe that there was a relationship between fuel volume and the altitude achieved by the rocket and, based on these observations, they reasoned that with higher fuel volume, the rocket could reach a higher altitude. Although they were not certain, they believed the bottle should be entirely full of fuel. Hence, they wanted to fix the volume of the mixture as high as possible.

Clearly, the students understood what they wanted to do, but the H2 they wrote conveyed something different. With a little effort, the students improved their technique for handling these variables when designing experiments and they made the necessary modifications to their experiment design (see the modified final proposal in Table A1).

Figure 1  Fin designs and sizes: FD1 (5cm) and FD2 (7.2 cm)

Hands-on activities and simulation models were excellent tools for helping the students internalize abstract concepts. With simulation, for example, students were able to verify or refute hypotheses and to manipulate variables. The activities helped them gain a deeper understanding about the control and manipulation of factors, observing results when factors were allowed to vary or were held constant. The activities also helped them to articulate and refine their mental models. Rocket Power, for example, learned that in their
experiment, density and volume had to be fixed. As a result, they fixed the proportion of warm water to soda in their mixture (8oz to 4oz), as well as the volume of fuel for each launch test, which was set at 12oz. Similarly, students realized the number of fins, their location on the rocket, and the distance from each other also had to be fixed in both prototypes in order to improve the usability of the experimental results. They fixed these values accordingly (Table A1).

Finally, we reviewed the students’ experimental plans. A number of relevant factors were not explicitly considered in their initial plans. Examples include: specifications of the size of the bottle, nozzle diameter, cone specification, materials for the fins and cone, fuel temperature, psi, number of experimental runs or replication, and methodology for measuring the rocket’s flight altitude. After performing the different exercises, the students were familiarized with the handling of the factors and, after some discussion, it was clear that they had formed mental plans to address this problem in their experiments. However, it was not yet completely clear to them that relevant variables of an experiment – controllable, non-controllable, and fixed – must be explicitly addressed in the experimental plan, and they resisted this requirement. Writing these kinds of details seemed overwhelming to the students, or perhaps they were approaching their academic limit. We were also short on time. Thus, the final experimental plans were incomplete; some important details were missing and others were vague. Rocket Power’s final hypotheses are presented below. The complete experimental plan, as submitted, is explained in Table A1. The important information missing from their plan relates to the randomization of the experiments, the number of experimental runs, and the replication.

H1: The fin design affects the stability of the rocket in flight.
H2: The rocker achieves a higher altitude with a fuel mixture of warm water and soda than it does with only warm water.

The team Rocket Power designed a 2^2 experiment – two-factor experiment involving fin design and fuel mixture, each with two levels - FD1 and FD2 for the fin design (Figure 1); and warm and warm water + soda for the fuel mixture (Figure 2) – to verify or refute H1 and H2. They conducted four experimental runs, one for each combination of levels, as shown Figure 2. There was no replication. The team took two measurements of the angle formed by the rocket flight path, using the Altitude Tracking Device; and a measurement of the rocket flight time, using a stopwatch, for each run. The average angle measurements and the estimated altitudes, as reported, are shown in Figure 2. The altitudes were determined using Eq.2 with a 18 m baseline.

\[ \text{Altitude} = \text{Baseline} \times \tan(\text{Angle} \times x) + 2.5 \]

Rocker Power found, as reported, that the bottle rocket achieved greater stability or precision during flight with the triangular fin design FD1 and a higher altitude (104.58 m) with the combination of factor levels: warm water plus soda (Sprite) and FD1, as shown in Figure 2. The rocket achieved its maximum altitude in 1:10 seconds. The total flight time for the rocket (from launch to return to earth) was 2:19 seconds.
A language-infused approach to introduce Dominican high school students to the logical process of designing experiments to construct knowledge.

**Figure 2** A two-factor factorial experiment involving fuel mixture and fin design. Value in ( ) is altitude in meters. Value outside ( ) is average angle measurement in degrees.

This analysis is clearly incomplete. For example, it does not include Estimation of the factor effects and basic descriptive statistical analysis. These and other basic analysis of experiment results can be considered in the future. Our main goal for this project, however, was to engage the students in the creative and logical process of designing an experiment rather than following instructions. This goal was accomplished fairly well, but a lot of improvement is still possible. Considering the works performed by all the teams, the results show a good evolution in their thinking and understanding of experimentation and research concepts over the period. Other teams produced similar factorial designs and analysis as Rocket Power. Their works went through similar evolution.

**Final remarks, challenges, and future work**
This project demonstrates that high school students can take an active role in the process of learning and that students with limited skills can gain a strong understanding of complex DAE principles and concepts when they are engaged in exploring and refining their mental models. The language-infused approach is challenging, however. It is time-intensive. There are moments when stepping back and letting the students find the answers or discover their misconceptions themselves can be difficult. The students can become frustrated, as well. But in the end, this type of approach can work well.

This approach has other limitations. It is not realistic to assume that students have the knowledge or skills necessary to solve all problems. It is, therefore, necessary to be flexible and anticipate possible areas of difficulties to provide better guidance. The
A language-infused approach to introduce Dominican high school students to the logical process of designing experiments to construct knowledge

objectives of the course must be specified. In this case, for example, the mechanics of analysis was not the main goal. The objective of this project was to immerse students in the logical process of designing experiments and to drive them to realize how and why scientists and engineers use experiments to build knowledge. We believe we accomplished this objective, despite the constraints mentioned. The students involved in the pilot project produced simple but well-designed experiments. They learned about rocket science and developed a broader and more sophisticated understanding of research. In addition, they gained valuable experience articulating and refining their mental models; thinking deeper about views and ideas; working in collaborative teams; and assisting one other with the learning process.

There were obviously significant challenges with the implementation of this curriculum. Time was perhaps the most significant barrier. This project was too ambitious, and it was highly time-intensive. It required significantly more than 36 hours for better implementation. Coming into the project, the students had no experience with research or experimentation, their math and language skills had limitations, and they needed more time for some activities than planned. Other constraints included lack of internet access, language barriers, and lack of electricity. Quality resources freely available on the Web, such as simulation models and other software, could not be used due limited internet access. It was difficult to find adequate learning resources in Spanish, and there was limited time and resources for producing extensive translations of other available resources. Thus, it was necessary to prepare some Spanish handouts in advance, but these were not as rich as the original sources. The language barrier limited the resources we could make available to the students for them to conduct research. Lack of electricity limited the time the students had to use the computers to practice with the simulation models.

Despite these challenges, the approach followed in the implementation of the language-infused curriculum proved challenging and exciting for all involved. The students developed agility over time and had fun learning, though they faced considerable mental blocks in the beginning. At first it was difficult for most students to articulate their ideas in writing. They also required considerably more time than available to properly learn the mathematic and statistic concepts we wished to use in the experiments.

**Future work:** To continue this project in the future, we plan to make necessary improvements to the course design and to perform at least one more pilot evaluation with high school students, where we would allot a five-week period for the project and would control for some of the constraints previously detailed. We also plan to adapt the program for college students.
A language-infused approach to introduce Dominican high school students to the logical process of designing experiments to construct knowledge

References


Shumway et al. (2010). A collaborative effort to teach technology and engineering concepts to middle school and high school students in the Dominican Republic. *ASEE Proceedings*, Louisville, KY, June 2010.


Jamison, J B (2006):. Research Methods in Psychology for High School Students, iUniverse Inc., NY


A language-infused approach to introduce Dominican high school students to the logical process of designing experiments to construct knowledge


A language-infused approach to introduce Dominican high school students to the logical process of designing experiments to construct knowledge

**APPENDIX I**

Table A1

<table>
<thead>
<tr>
<th>Rocket Power Experiment Planning Evolution</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initial Proposal</strong></td>
</tr>
<tr>
<td>Research question/hypothesis</td>
</tr>
<tr>
<td>RQ1 Will soda produce more pressure than water</td>
</tr>
<tr>
<td>RQ2 The size of the wings together with the soda as fuel will produce a higher impulse in less time</td>
</tr>
<tr>
<td>Experimental plan</td>
</tr>
<tr>
<td>We will two rocket prototypes, one with big wings and soda for fuel and the other with small wings and water then exchange the fuel</td>
</tr>
<tr>
<td>Factor and level</td>
</tr>
<tr>
<td>Controllable</td>
</tr>
<tr>
<td>1 Fuel mixture</td>
</tr>
<tr>
<td>Warm water</td>
</tr>
<tr>
<td>Warm water plus soda</td>
</tr>
<tr>
<td>2 Wing design</td>
</tr>
<tr>
<td>WD1 (5.0 cm)</td>
</tr>
<tr>
<td>WD2(7.2 cm)</td>
</tr>
<tr>
<td>Factor specifications</td>
</tr>
<tr>
<td>Wing material: heavy carton</td>
</tr>
<tr>
<td>Location of wing: bottom of rocket</td>
</tr>
<tr>
<td>Space between wings: equal</td>
</tr>
<tr>
<td>Fuel volume: 12 oz</td>
</tr>
<tr>
<td>Fuel mixture proportions: warm water (8oz) and Sprite (4oz)</td>
</tr>
<tr>
<td>Water temperature: will warm up with the sun</td>
</tr>
<tr>
<td>Other factors</td>
</tr>
<tr>
<td>Bottle size: 16 oz</td>
</tr>
<tr>
<td>Bottle material: plastic</td>
</tr>
<tr>
<td>Pressure: 90psi</td>
</tr>
<tr>
<td>Rocket materials</td>
</tr>
<tr>
<td>We will use available materials</td>
</tr>
<tr>
<td>Plastic bottle - 16oz or 20oz</td>
</tr>
<tr>
<td>Carton</td>
</tr>
<tr>
<td>Constraints</td>
</tr>
<tr>
<td>Time</td>
</tr>
<tr>
<td>Materials</td>
</tr>
<tr>
<td>Performing the experiment</td>
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22