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PIRPOSAL model of integrative STEM education:

CONCEPTUAL AND PEDAGOGICAL FRAMEWORK FOR CLASSROOM IMPLEMENTATION

BY JOHN G. WELLS

The premise of I-STEM ED requires a blended… approach intent on teaching other expressly targeted STEM content and practices.

The integration of science, mathematics, and technology (SMT) in K-12 education has been a national priority since the Excellence Reform Movement took root in the 1980s, and was given voice beginning as early as 1983 through publications such as *A Nation At Risk, Science for All Americans, Benchmarks for Science Literacy,* and *Rising Above the Gathering Storm* (Wells, 2008, p. 3). That priority has more recently included engineering education, which now is reflected by the "E" in STEM. The continued emphasis on the integration of these four subject areas collectively embodies what today is recognized as STEM Education Reform, and in 2006 was the context and impetus for introducing Integrative STEM Education at the state level. Nationally in 2010 the international association for teachers of technology education formally changed its name to the International Technology and Engineering Educators Association (ITEEA). Concurrent with its name change, ITEEA began characterizing Technology and Engineering Education (TEE) as an "integrative" endeavor and reflecting the concept of Integrative STEM Education (I-STEM ED) as proposed at Virginia Tech, which today is defined as:

> "…the application of technological/engineering design-based pedagogical approaches to *intentionally* teach content and practices of science and mathematics education through the content and practices of technology/engineering education. Integrative STEM Education is equally applicable at the natural intersections of learning within the continuum of content areas, educational environments, and academic levels" (Wells & Ernst, 2012/2015).

By definition, I-STEM ED is a pedagogical approach for supporting knowledge construction through student engagement in technological/engineering design-based learning. The pedagogical premise is that of connecting hands-on with minds-on, where hands-on experiences are intentionally utilized to achieve minds-on learning outcomes; i.e., experiential learning intentionally used to promote knowledge construction (Kolb, 1984). Absent however are instructional models that emphasize the knowing that should result from having engaged the learner in technological/engineering design-based learning.

STEM EDUCATION: MODELS OF CONTENT AND PRACTICES

The fundamental goal of any pedagogy is to guide the learner toward achievement of a learning outcome, be it cognitive, behavioral, or a combination of both. In K-12 education this translates into what students should know and be able to do. Student achievement of these learning outcomes is intended to develop within the learner habits of both mind and hand characteristic of disciplinary practices as established by state and national standards.

The pedagogical characteristics of K-12 STEM disciplines are illustrated through instructional models thought to best represent the signature practices of that discipline. However, implementation of these discipline-specific models is problematic because they are associated not only as a method for teaching the ***content*** of a discipline (habits of mind), but also a method for teaching the ***practice*** of a discipline (habits of hand). Close inspection of these models reveals that they fall well short of achieving either, and are not adequate for conveying an integrative teaching approach to STEM education.

SCIENCE EDUCATION INQUIRY MODELS

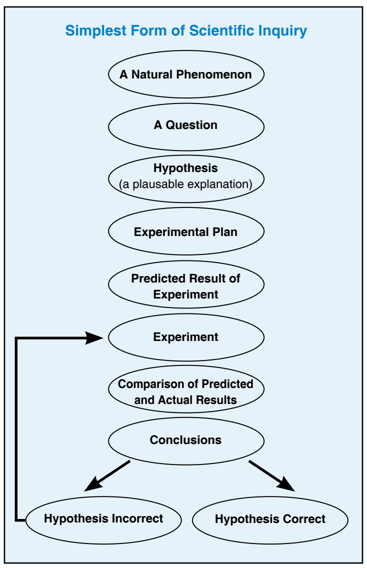


Figure 1. Scientific Inquiry.

In science education the traditional model used to convey the process of scientific inquiry has been one where the scientific method is depicted as a linear process with a prescribed series of steps scientists follow when investigating the cause-and-effect relationships of a natural phenomenon (Fig. 1). This linear model has been, and in many instances still is, what K-12 students are taught when learning to practice as would a scientist. However, a study in 2002 by Harwood, Reiff, and Phillipson investigating the actual practices of more than 50 scientists found they follow a much more fluid approach. Based on their research, the model they developed (Fig. 2) better illustrates what most closely resembles the actual practice of scientific inquiry. More recently, with the advent of *Next Generation Science Standards* (*NGSS*) (Lead States, 2013), additional models have been introduced in science education that attempt to clarify the incorporation of engineering design as a new strategy for teaching scientific inquiry. Appendix I – Engineering Design in *NGSS* introduces an additional model intended to convey how "the core idea of engineering design includes three core component ideas" (p. 2) identified as (1) Define engineering problems, (2) Design engineering solutions, and (3) Optimize the engineering solution. This one model is used repeatedly (pp. 3-6) across four grade bands to convey increasing levels of complexity for core engineering ideas introduced at successive grade bands (Fig. 3). As a problem-solving model it is not an intuitive mechanism to describe how students will "explicitly learn how to engage in engineering design practices to solve problems" (p. 2). Inclusion of engineering in *NGSS* has also spurred other linear models attempting to embed engineering into science education (Fig. 4). These additional models add to the confusion regarding just what scientific inquiry practices students should know and be able to do. Regardless of which model is used in science education, the intent is to convey the practices of their discipline—science. There is no expressed intent to teach other disciplines, nor an integrative approach for concurrently teaching content and practices of those disciplines.

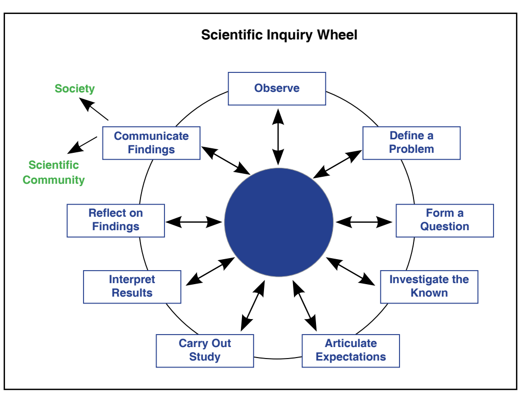


Figure 2. Inquiry Wheel.

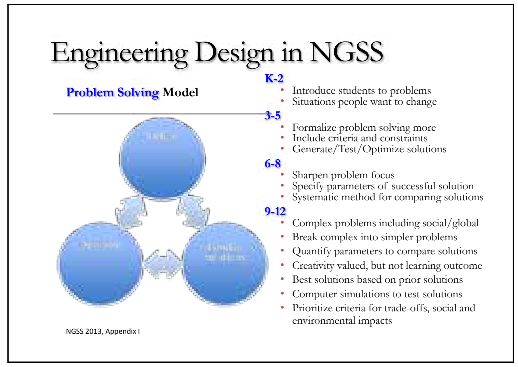


Figure 3. *NGSS* Engineering Design

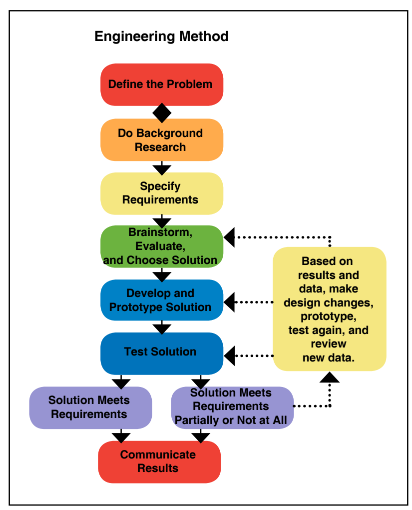


Figure 4. Engineering in Science

TECHNOLOGY AND ENGINEERING EDUCATION MODELS

In K-12 Technology and Engineering Education (TEE), the traditional models used to illustrate technological and engineer-

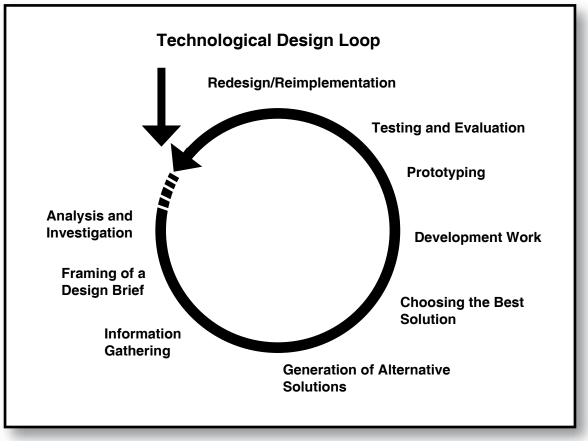


Figure 5. Classic Technological Design Loop

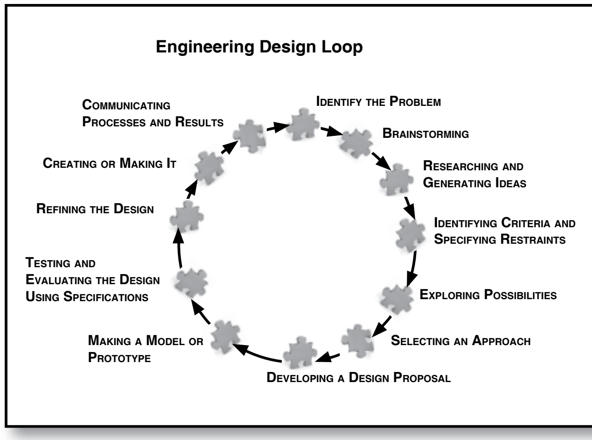


Figure 6. Typical Engineering Design Loop

ing content and design practices are shown in Figures 5 and 6. The classic Technological Design Loop (Fig. 5) has been recast in many ways over the past few decades, but the basic circular representation of practices as a series of steps involving the technological design process has remained consistent. Similarly, the Engineering Design Loop (Fig. 6) depicts many of the same practices but incorporates additional steps thought to be more specific to engineering. Regardless of which model is used, all visually convey design as a circular cycle of practice to be taught and employed by the teacher when engaging students in designing engineering solutions. Of significance to the TEE educator is what the models also imply regarding content and practices of other disciplines. Unique among the STEM education disciplines, TEE is well positioned to serve as an integrator of knowledge from other subject areas. Recognition of this potential for integrative teaching of other STEM content and practices through TEE design is specifically addressed on pages 28-29 of *Technology for All Americans: A Rationale and Structure for the Study of Technology* (ITEA/ITEEA, 1996/2005), and pages 6-9 of *Standards for Technological Literacy: Content for the Study of Technology* (*STL*) (ITEA/ITEEA, 2000/2002/2007). However, the current TEE models are not adequate in conveying the concepts or methods to implement such integrative STEM education approaches.

INTEGRATIVE STEM EDUCATION MODELS

Unlike the traditional monodisciplinary approach for teaching TEE, the premise of I-STEM ED requires a blended pedagogical approach intent on teaching other expressly targeted STEM content and practices. By definition and in practice, the implementation of I-STEM ED will therefore be distinctly different pedagogically from that which has been traditionally conveyed in either the Technological Design Loop (Fig. 5) or Engineering Design Loop (Fig. 6) models. Furthermore, all prominent K-12 STEM education models depict their discipline-specific content and practices largely emphasizing lower-order procedural and declarative cognitive demands. And notably not conveyed within the TEE models are those instances where TEE design-based learning (DBL) will naturally impose higher-order schematic and strategic cognitive demands (Wells, 2014).

Given that traditional STEM education models will not suffice in conveying an integrative approach, what models are available that do represent and convey the conceptual and/or pedagogical approach of Integrative STEM Education? Specifically, what models are explicit in illustrating the amalgam of pedagogies to be employed when using Integrative STEM Education to teach the full spectrum of STEM content and practices inherent within TEE DBL? STEM educators will need a model that accurately conveys how I-STEM ED is to be conceptualized and pragmatically implemented in the K-12 classroom. Grounded in a decade of I-STEM ED instructional design and development, the PIRPOSAL Model© (Wells, 2015) is proposed as one that can fulfill this need (Fig. 7).

In the following pages, this first of two articles explains the conceptual framework regarding how components of the PIRPOSAL model convey theory to practice. The second article will follow at a later date with an I-STEM ED exemplar to demonstrate pedagogical methods for classroom implementation.

PIRPOSAL MODEL: THEORY TO PRACTICE

In Theory: Conceptual Framework of Integrative STEM Education

The primary instructional goal of I-STEM ED is to teach students both content and practices of TEE design, but with equal intent on teaching other inherent science and mathematics content and practices. The I-STEM ED approach is therefore also obligated to intentionally employ appropriate pedagogical practices when teaching and assessing the respective content and practices of individual STEM disciplines. The current monodisciplinary STEM models do not capture the true nature of I-STEM ED, and therefore cannot serve as a framework for conveying the integration of concurrent pedagogies. The PIRPOSAL model embraces this concurrence and is deliberate in their employ to teach not only TEE content and practices, but those of other inherent disciplines.

As conveyed through the PIRPOSAL model, engineering design is represented as ***phases of engagement*** encountered by the designer when attempting to resolve an engineering challenge. Conceptually, the PIRPOSAL model illustrates the ways in which engineers work and think, their "designerly ways of knowing" (Cross, 1982), while engaged in the design of an engineering solution. As an instructional approach I-STEM ED is intent on exploiting the full spectrum of complex learning processes uniquely associated with knowledge acquisition through engineering-design-based learning. The PIRPOSAL model illustrates how engineering design is used to intentionally promote the higher-order thinking (schematic and strategic knowledge) necessary for students to gain deep understanding of STEM content and practice. Specifically, I-STEM ED uses design-based learning with the expressed intent of having students *design to understand* (D2U).

Pragmatically, the eight PIRPOSAL phases intentionally position a student's achievement of understanding within the "need to know" context imposed by the challenge of designing an engineering solution (Wells, 2014). Driven by the need to know, questioning is the central factor determining which phase students will engage in throughout the engineering design process. As such it is important to recognize that, from a D2U instructional perspective, the phases of the PIRPOSAL model are not to be construed as a series of steps a learner commits to memory as procedural knowledge and then follows ritually with little cognitive demand (McCormick, 2004). To the contrary, each phase reflects the designerly focus of student engagement as derived from the particular questions the student designers ask themselves regarding what they need to know at any given point in the design process. Basing the organization of phases on a student's "need to know" prompts teacher recognition of the types of questions learners should and/or will typically encounter throughout the various design transitions. This recognition affords teachers the opportunity to prepare for student questions and/or to provide appropriate prompts to guide learners toward integrative understanding of targeted STEM content and practices.

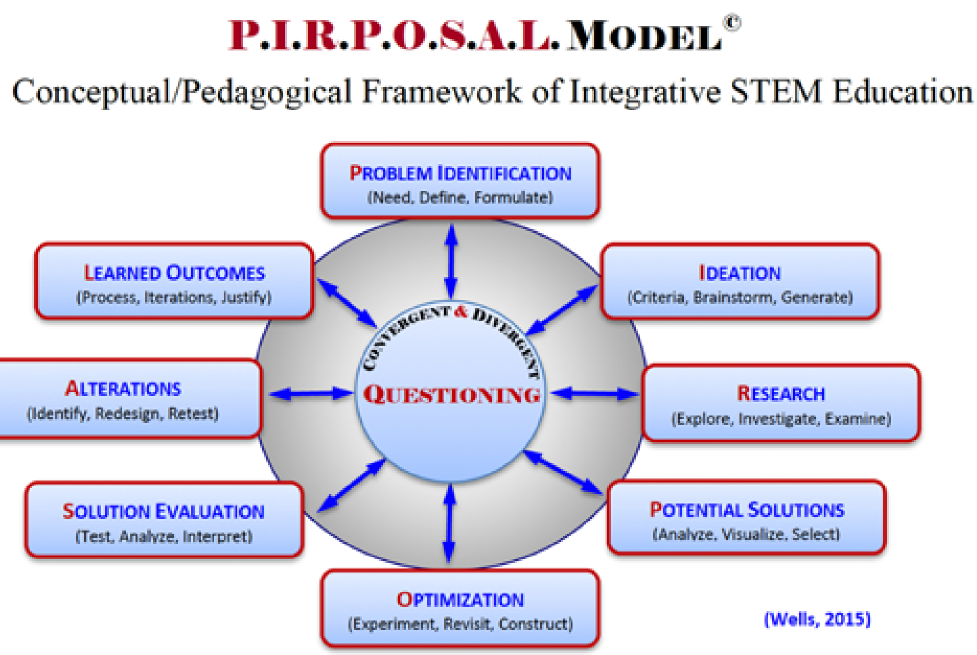
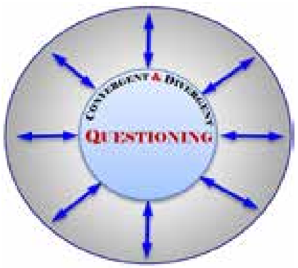


Figure 7. PIRPOSAL Model of Integrative STEM Education

Theory to Practice: Classroom Implementation of Integrative STEM Education

Implementation of I-STEM ED based on the PIRPOSAL model is best illustrated through discussion of its individual components just as a learner would engage in them when working toward an engineering design solution. It is important to clarify that the model is being presented sequentially for convenience purposes only. In practice this would not naturally be the case, as starting points in a design process are fully dependent on designerly questioning. The discussion therefore begins with the centrality of questioning followed by how that guides students through the eight phases of design.

Centrality of Questioning.



Question posing initiates all engineering design processes. Regardless of which design phase the learner finds him or herself engaged in, he or she is confronted with a need to know that, in turn, elicits designerly questioning. Knowledge resides within the questioning, with lower-level questions necessarily preceding the deeper reasoning questions reflective of designerly thinking (Cross, 2001). Initial lower-level questioning draws on the learner's resident knowledge to determine what he or she currently knows about a given topic. His or her resident knowledge serves as initial building blocks, leading to follow-on questions regarding what he or she still needs to know. The new questions reveal additional required knowledge needed to move forward in the design process. Questions derived from resident knowledge exhibit ***convergent thinking*** on the part of the learner as attempts are made to pull together factual and verifiable information. As the learner synthesizes this body of knowledge, he or she begins posing "what if" questions and diverging from the factual information. The student designer engages now in ***divergent thinking*** that discloses questions for which he or she does not as yet have answers. Confronted by new concepts, the learner must reconsider what he or she already knows about that concept in order to advance understanding. New understandings allow the learner to then generate alternative plausible solutions to address a design need. This progression from convergent to divergent designerly questioning involves a series of ongoing transitions between knowledge and concept domains (what I know and what I need to know) that ultimately results in design decisions. Thus, learner questioning and Engineering Habits of Mind facilitate transitions among the various phases of engineering design.

P.I.R.P.O.S.A.L. Phases.

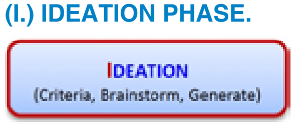
Every PIRPOSAL phase is comprised of three designerly questioning focal points, each of which highlights the intentional integration of specific designerly practices. The following are details regarding how designerly questioning guides the student designer within a given phase throughout a design challenge.

(P.) PROBLEM IDENTIFICATION PHASE.

DESIGNERLY QUESTIONING Focal Points: Need, Define, Formulate

The primary goal of engineering is to design a solution that meets a social (human) need[1], and as a learning outcome, achieving that goal is pedagogically unique to technology and engineering education (TEE). Consequently, the TEE educator initiates instruction with a focus on the human/social need to be met. Need is the opener for student designerly questioning and that which the educator employs to guide student designers in first recognizing and then expressing what is understood to be the social/human need requiring an engineering solution. Based on initial understanding, the educator prompts the student designer to operationally ***define*** the problem in order to clarify why it is that an engineering solution is required. Building on that operational definition, the student designer can then ***formulate*** a concise statement of the problem within the context of the engineering design challenge. Problem formulation involves synthesis questions based on design specification details (need + problem) that culminate in the designer's clear statement regarding the function the engineering solution must perform. In formulating the problem statement, the student designer refers to the Design Challenge, which outlines the specific criteria, parameters, and constraints as dictated by both the context and desired function of the engineering solution. Criteria can be defined as principles or standards by which the performance of something is judged, parameters as the set of limitations imposed by the context or client, and constraints as those variables the designer cannot control and that therefore restrict a design process (such as cost, environment, required space, specified materials, biological capabilities, etc.). The student designer formulates, as the problem indicates, the specifications of what, at this early point in the design process, he or she has come to understand is required for a viable solution. As they progress through the various design phases, knowledge gained through designerly questioning will return them often to the first phase to revisit what they initially identified as the problem.

(I.) IDEATION PHASE.



DESIGNERLY QUESTIONING Focal Points: Criteria, Brainstorm, Generate

Ideation is typically a group creativity process occurring in tandem with the *Research Phase* because it requires some degree of concurrent investigation to learn about variables

[1] The need to be met through engineering design is a social/human one. This is distinct from, and not to be confused with, an individual's need.

that may affect, or are affected by, the problem. Ideation begins with a review of the ***criteria*** contained in the information gathered during the *Problem Identification Phase* (parameters, constraints, etc.). This review reveals to the student designers what they (a) know about the problem and (b) need to know about it. Engaging first in convergent questioning, student designers discuss what they currently know about the problem and use that discussion to solicit ideas from all members of the group regarding possible design solutions. While ***brainstorming***, student designers also recognize the areas in which they lack knowledge and which will require further investigation on their part regarding the need to know about certain design variables. This open exchange of thoughts spawns many plausible ideas, each of which prompts divergent questioning on the part of the student designer in conceptual attempts to address "what if" alternative solutions. During the *Ideation Phase,* team members record all suggestions and/or recommendations, including any sketches, drawings, or notes relevant to potential designs, which together result in the ***generation*** of one or more initial plausible design solutions.

(R.) RESEARCH PHASE.

DESIGNERLY QUESTIONING
Focal Points: Explore, Investigate, Examine

This phase of questioning results in a synthesis of information students use to design the various components of their potential solutions. Driven by divergent questioning from the *Ideation Phase*, students ***explore*** their particular engineering topic to learn which components and/or techniques may prove useful within the novel context of their design challenge. Explorations are followed by in-depth ***investigations*** of prior solutions that hold promise, and to better understand the individual components and techniques used. These investigations lead to the acquisition of new knowledge, not only in design, but within the full spectrum of science, technology, engineering, and mathematics subject areas. Generated by an ongoing iterative process of convergent and divergent questioning, newly acquired knowledge in turn provides the student designer with the cognitive tools needed to conceive of viable alternative designs. Knowledge gained in researching how others have previously addressed the problem develops within the learner the integrative STEM understanding necessary for designerly thinking.

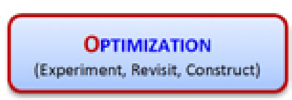
Fostering designerly thinking is central to the I-STEM ED approach, given the intent is to teach not only TEE content and practices, but those of the other STEM disciplines as well. During the *Research Phase* this requires the educator to design instruction and strategies in a way that will ensure that students focus their investigations on discipline-specific content and practices intentionally being targeted as learning outcomes. To do so, the educator has students ***examine*** separately the science, technology, engineering, and mathematics associated with each component required of an acceptable design solution. Such an examination is particularly important for promoting student understanding of the design constraints naturally imposed by various STEM elements inherent within any engineering design challenge.

(P.) POTENTIAL SOLUTIONS PHASE.

DESIGNERLY QUESTIONING
Focal Points: Analyze, Visualize, Select

Armed with ideas and knowledge gained from the brainstorming and research phases, the student designer is in a position to move ahead with determining which potential solutions are viable options. The initial learner task during the *Potential Solutions Phase* is to ***analyze*** the various discipline-specific elements of a potential solution. Convergent questioning is prominent during analysis where the student designer considers what he or she knows about the potential solutions—technologies, materials, processes, etc.—necessary to support each component or system within it. When enough information has been gathered through this line of questioning to justify a decision, the designer selects those alternative solutions that best fit the problem. Analysis of each design option continues through development of detailed sketches, allowing the designer to ***visualize*** alternative solutions. In generating sketches and drawings, the student designer gives substance to his or her ideas—different sizes, shapes, environments, systems, organisms, materials, etc., which serve as the basis for making informed decisions and resulting in ***selection*** of one or more potentially viable design solutions.

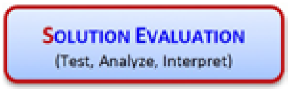
(O.) OPTIMIZATION PHASE.



DESIGNERLY QUESTIONING
Focal Points: Experiment, Revisit, Construct

Optimization of potential designs is to a large extent guided by divergent questioning as the student considers and explores essential design components. Assessment of components is often accomplished through ***experimentation*** to determine how well they function within any of the selected potential designs. The designer uses these results to ***revisit*** a particular design direction and assess how well that component helps meet the design criteria. Additional considerations would include variables such as costs (time, resources, production), impacts (environmental, sociocultural, political), and product disposal at the end of its useful life cycle. Based on these assessments, the student designer determines which combination of components within a potential solution provides the optimum fit for addressing the problem. Design questions addressed during the *Optimization Phase* lead to a final design solution in which the student can be confident enough to begin prototype ***construction***. In the PIRPOSAL model, the constructed prototype is envisioned as a scaled, working model that attempts to have complete function, behavior, and structure of the intended engineering solution.

(S.) SOLUTION EVALUATION PHASE.



DESIGNERLY QUESTIONING Focal Points: Test, Analyze, Interpret

Intended to demonstrate a proof of concept, the prototype is used to ***test*** design concepts by conducting actual trials, collecting and ***analyzing data***, making observations, performing any necessary adjustments to the prototype, and drawing conclusions based on an ***interpretation*** of results. Designerly questions posed during the *Solution Evaluation Phase* will therefore be directed at evaluating individual attributes of the prototyped solution against each of the criteria described in the design challenge. This typically involves a series of sub-experiments to test each attribute and determine where the design exceeded and/or failed to meet specifications. Interpretation of quantitative and qualitative results are used in describing those design attributes that either failed or need to be addressed in any redesign of the solution. These interpretations have direct implications for making informed design alterations to improve the solution.

(A.) ALTERATIONS PHASE.

DESIGNERLY QUESTIONING Focal Points: Identify, Redesign, Retest

It is rare that initial designs are successful in meeting all design criteria. Invariably, performance issues accompany first attempts at designing viable engineering solutions, each of which generates a new line of designerly questioning. Questioning returns the student designer to results from the previous *Solution Evaluation Phase* where performance issues are ***identified*** in the initial prototype. Revisiting these results allows the student designer to isolate specific prototype attributes that did not meet specifications and are in need of ***redesign***. The need to redesign returns the student designer to previous phases where he or she will re-engage in respective questioning and design tasks. Ultimately, evaluation of the redesigned components will require each to be ***retested***, followed by an analysis of data and interpretation of results. Each successive iteration brings the student designer closer to a solution that meets the engineering design specifications.

(L.) LEARNED OUTCOMES PHASE.

DESIGNERLY QUESTIONING Focal Points: Process, Iterations, Justify

Knowledge resides within the designerly questions imposed by the engineering challenge and revealed in the answers student designers can provide. The *Learned Outcomes Phase* involves students communicating graphically, verbally, or in writing, what they have come to know and are able to do as a result of their engagement. This communication serves as an effective mechanism for revealing student development along the full continuum of high- and low-order thinking inherent to the cognitive demands imposed by engineering design (Wells, 2014). ***Process*** discussions are ideal for revealing learner gains in procedural and declarative knowledge required by the engineering design process. Discussion of ***iterations*** reveals the progression of lower-level questions that preceded the deeper reasoning questions, reflecting student transitions between convergent and divergent thinking. Students demonstrate their higher-order schematic and strategic knowledge when explaining connections between the content and practices utilized in making informed decisions and resultant understanding needed to ***justify*** any of their design directions. In the context of teaching both content and practices of TEE at the K-12 level, communication of knowledge and understanding acquired as a result of engineering design can be viewed as goals of both the engineering design and instructional processes. In meeting his or her instructional goals, the educator capitalizes on the *Learned Outcomes Phase* as one avenue for conducting both formative and summative assessment of student achievement of targeted learning outcomes.

SUMMARY: DESIGNERLY THINKING AND THE CENTRALITY OF QUESTIONING

The PIRPOSAL model is both a conceptual and pedagogical framework intended for use as a pragmatic guide to classroom implementation of Integrative STEM Education. Designerly questioning prompted by a "need to know" serves as the basis for transitioning student designers within and among multiple phases while they progress toward an engineering solution that will function as prescribed in the specifications of the social/human need. These transitions are both dynamic and fluid, engaging the learner for various intervals of time, from fleetingly considering a concept or idea to more lengthy periods of thoughtful attention, depending on the questions posed. In this way, driven by the centrality of questioning, the eight phases of the PIRPOSAL model reflect authentic designerly practices occurring in their natural, non-linear fashion based on the designer's need to know.

P.I.R.P.O.S.A.L. Model©

Conceptual/Pedagogical Framework of Integrative STEM Education

The second PIRPOSAL article in this series will use an I-STEM ED exemplar to discuss the way STEM education pedagogies are used to intentionally teach discipline-specific content and practices. As well there will be a discussion of how PIRPOSAL phases are used to structure engineering journaling that captures a student's designerly ways of knowing, from declarative to strategic, for use by the teacher in assessing their achievement of intended learning outcomes.

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