feature article


# I-STEM Ed Exemplar:
## Implementation of the PIRPOSAL Model

The opening pages of the first PIRPOSAL article make the case that the instructional models currently used in K-12 STEM Education fall short of conveying their respective disciplinary content and practices (Wells, 2016a, pp. 12-14). And because they are all siloed, monodisciplinary models, none present the concepts or practices of an integrative approach to STEM education. In contrast, within the context of technological/engineering design-based learning, the PIRPOSAL model embraces the concurrence of STEM subjects and makes explicit the Integrative STEM Education (I-STEM ED) approach for teaching and learning STEM content and practices. To support I-STEM ED teachers in moving past the traditional silo approach to STEM education, they need examples of instructional strategies designed to capitalize on the inherently integrative nature of technological/engineering design-based learning (T/E DBL).

To address that need this article presents an I-STEM ED exemplar as a vehicle for discussing how STEM education pedagogies can be used for intentionally teaching discipline-specific content and practices integral within the phases of technological/engineering design. As such, the purpose of the exemplar is to describe the instructional strategies of I-STEM ED as implemented through the eight phases of the PIRPOSAL model that directs student engagement in their design of T/E solutions. Pedagogically these strategies build on Gagne's events of instruction (2004) as derived from his cognitive learning theory of information processing and conditions of learning[1] and on Webb's Depth of Knowledge (1997) criteria[2] for as-


by
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[1] Refers to Gagne's nine events of instruction used as a framework to prepare and deliver content.
[2] Knowledge, as used in this article, refers to those forms encompassed by procedural, declarative, schematic, and strategic knowledge domains.

sessing student understanding as they react to the cognitive demands imposed on them during any of the eight phases of T/E design.

As in the first PIRPOSAL article, the implementation described here discusses each of the eight phases sequentially for convenience purposes only. In practice, however, the adept educator will deliver instruction based on knowledge of their students, the context of the teaching/learning environment, and the flow of students' designerly questioning.

## Design-Based Biotechnology

The exemplar selected for instructional illustration comes from Chapter 4 on Bioprocessing in the Design Based Biotechnology Literacy (DBBL) Teaching Guide (Wells, 2015a). The specific biotechnical design challenge is Problem Scenario 4A on Alternative Fuels, which challenges students with prototyping a continuous flow bioreactor as a proof of concept for demonstrating ethanol production from biomass as an alternative, renewable biofuel. Although the strategies described below are those used when teaching the Design Based Biotechnology Literacy course (EDCI 5854) to STEM classroom practitioners, it represents only one of several ways in which the PIRPOSAL model has been used to implement I-STEM ED in the classroom. As well, the level of detail that can be provided through this exemplar is constrained by the article length restrictions in this journal. As such, only a select few targeted learning outcomes will be used to illustrate the intentional teaching and assessment of content and practices. Identified in Figure 1 is a small sample of the targeted STEM content and practice learning outcomes possible, along with associated cognitive demands. Strategies used to intentionally teach the outcomes highlighted by bold text in the Content column (predictive analysis, bioprocessing, liquid and gaseous volumes) are those described in this article. And finally, to the extent possible, descriptions and images are provided to reflect how both teaching and learning is facilitated as students progressed toward development of a working bioreactor prototype.

### Intentional Learning Outcomes

| Discipline | Content | Habits of Mind (cognitive demands) | Habits of Hand (practice) |
|---|---|---|---|
| **Engineering** (primary) | Engineering Design<br>- **Problem Identification**<br>- **Predictive Analysis**<br>- Optimization | Need/Define/Formulate<br>Quantity of Products Produced<br>Adequate System Size | Design/Prototype/Test |
| **Technology** (primary) | Biotechnical Systems<br>- Continuous flow<br>- **Product Separation**<br>- Microbial Requirements | Define/Process/Materials<br>Products/Methods/Immobilization<br>Nutrients/Environment | Design/Prototype/Test |
| **Science** (concurrent) | Microbes<br>Biomass<br>**Bioprocessing**<br>**Chemical Composition** | Morphology<br>Energy Source<br>REDOX<br>Atomic Mass/Output Potential | Experimental Design<br>Data Collection/Analysis |
| **Mathematics** (concurrent) | **Volume (liquid vs. gas)** | Ethanol (liquid volume)<br>Carbon Dioxide (gaseous volume) | Experimental Design<br>Data Collection/Analysis |

**Figure 1:** Sample of targeted learning outcomes.

## Implementing the PIRPOSAL Model

Central to implementing the PIRPOSAL model (Fig. 2) is question posing, which both initiates and directs all engineering design processes and is therefore integral in the teacher's design of instruction. Questioning can and will come from both teacher and student alike depending on classroom dynamics and instructional preferences. From the student perspective, questioning will reflect ongoing cognitive transitions between what they know (convergent questions/knowledge domain) and what they need to know (divergent questions/concept domain) regarding the design challenge, which together empowers them to make informed design decisions. These cognitive transitions develop

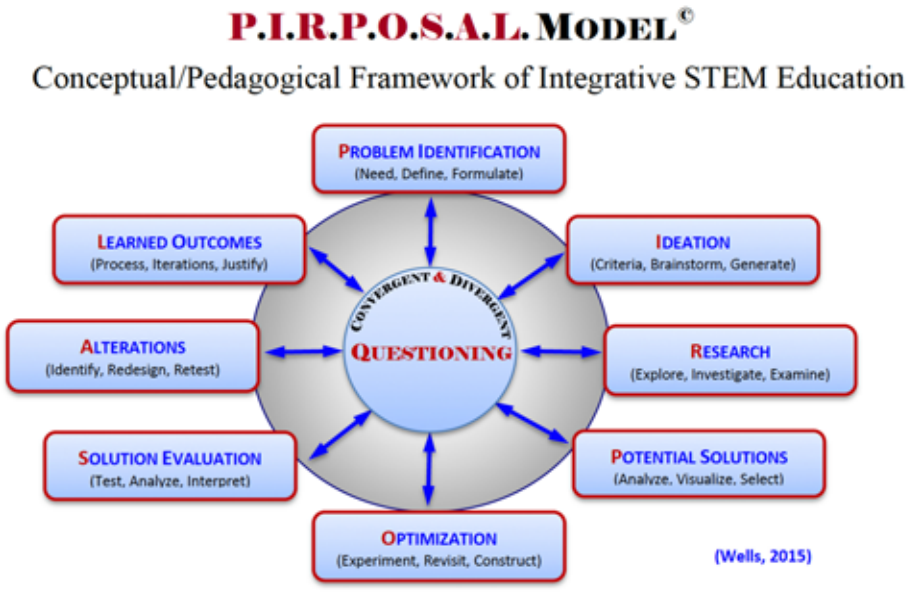



**Figure 2:** PIRPOSAL Model for I-STEM ED.

the learner's Designerly Ways of Knowing (Cross, 1982) and his/her achievement of true understanding—the explicit instructional goal for having students Design to Understand© (D2U©). From a teacher perspective, questioning presents opportunities for both formative and summative assessment of the instructional strategies they chose. Teachers depend on the questions students ask for knowing how well their choice of strategies is promoting the intended student learning throughout the phases of T/E design.

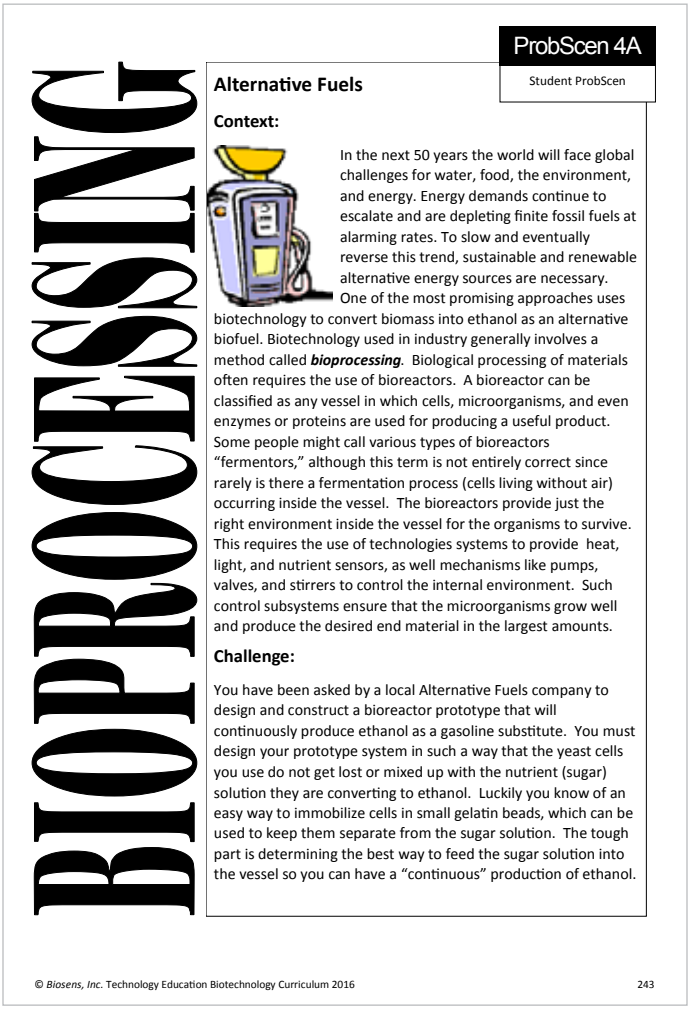
As explained in the first article, in each of the eight PIRPOSAL phases three key questioning prompts serve as Designerly Focal Points (DFP) that initiate student engagement in any given phase of T/E design. In the descriptions that follow, the teaching strategies for each PIRPOSAL phase will include discussion of how DFPs are used to engage students in the design process through questioning. Documentation of student engagement is facilitated through student use of an Interactive Engineering Journal (IEJ), which in the DBBL course is a bound composition book where pages are neither removed nor added.

As the name implies, the IEJ is an interactive tool that students use for documenting their engagement throughout all phases of design. Introduced by the teacher as a daily design tool, students view it as just another tool they need and use while working toward an acceptable T/E design solution. Each day that students work on their design challenge they begin by adding the current date just beneath the last entry in their journal. The date is followed by the question(s) they next want to answer (or continue to answer) regarding the current phase of design. (Note: Student entries in the IEJ are done in ink to ensure all ideas are captured and none lost as a result of erasing.) Inside the front cover of the IEJ students tape a copy of the PIRPOSAL phase descriptions. This copy of the eight design phases serves as a reference providing the context for the designerly questions students encounter during any phase of design. This context helps scaffold student understanding of the content and concepts imposed by the design challenge, and recognize connections needed to make informed decisions about their design solution. As a student-centered tool, the IEJ is a record of their design journey. As a teacher-centered tool, it is a record useful for evaluating achievement of both curricular and pedagogical goals.

## Recognize Human Need, Operationally Define and Formulate the Problem

In the teaching episode that begins the Problem Identification Phase (DFP: Need, Define, Formulate) the teacher uses a strategy designed to gain student attention and ready them for engaging in the teaching/learning process. An opening question related to local/global energy needs is posed by the teacher in any number of ways (chalkboard, whiteboard, smartboard, tablet, etc.). Her question is presented together with (or preceded by) something that will generate surprise and uncertainty about the connections between current and future problems regarding local and global energy needs; e.g., a recent news clip, YouTube video, etc. The teacher follows this with further questioning intended to help students recognize that the need is one that addresses the larger human, sociocultural issue, and to make clear that it is not one specific to the individual. At this point students are directed to open their Interactive Engineering Journals (IEJ) to their last entry, and on a new line begin their journaling by recording the date. Beneath the date students are asked to write what they understood to be the human need just discussed. When all have finished writing, the teacher asks the class to guide her in writing on the board a complete statement capturing their understanding of the energy need.

The completed need statement is used to guide student discussion toward justifying why it is that an engineering solution is the appropriate choice for addressing this particular energy need. In this way students are helped to operationally define the problem, with the teacher using their input to formulate a clear statement of that problem within the context of the engineering design challenge. This discussion involves a series of synthesis questions that bring to light the main design specifications (need +


BIOPROCESSING

ProbScen 4A

Student ProbScen

**Alternative Fuels**

**Context:**

In the next 50 years the world will face global challenges for water, food, the environment, and energy. Energy demands continue to escalate and are depleting finite fossil fuels at alarming rates. To slow and eventually reverse this trend, sustainable and renewable alternative energy sources are necessary. One of the most promising approaches uses biotechnology to convert biomass into ethanol as an alternative biofuel. Biotechnology used in industry generally involves a method called ***bioprocessing***. Biological processing of materials often requires the use of bioreactors. A bioreactor can be classified as any vessel in which cells, microorganisms, and even enzymes or proteins are used for producing a useful product. Some people might call various types of bioreactors "fermentors," although this term is not entirely correct since rarely is there a fermentation process (cells living without air) occurring inside the vessel. The bioreactors provide just the right environment inside the vessel for the organisms to survive. This requires the use of technologies systems to provide heat, light, and nutrient sensors, as well mechanisms like pumps, valves, and stirrers to control the internal environment. Such control subsystems ensure that the microorganisms grow well and produce the desired end material in the largest amounts.

**Challenge:**

You have been asked by a local Alternative Fuels company to design and construct a bioreactor prototype that will continuously produce ethanol as a gasoline substitute. You must design your prototype system in such a way that the yeast cells you use do not get lost or mixed up with the nutrient (sugar) solution they are converting to ethanol. Luckily you know of an easy way to immobilize cells in small gelatin beads, which can be used to keep them separate from the sugar solution. The tough part is determining the best way to feed the sugar solution into the vessel so you can have a "continuous" production of ethanol.

**Figure 3:** ProbScen 4A Context & Challenge.

problem) and lead students to a better understanding about the functions their engineering solution must perform. Building on student input, the teacher crafts the problem statement on the board. When agreement on the statement is reached, students record it in their journals.

Considering the functions their engineering solution is supposed to perform, students are asked to think about what they see as possible design requirements (parameters/place, restrictions, and constraints) and list them in their IEJ directly beneath the problem statement. As a group, the teacher then asks them to share their lists while she records each unique criteria on the board. Collaboratively, a final problem statement is generated that includes both the context and specifications (criteria) of the engineering design challenge. The teacher prints a copy of the context, problem, and challenge for each student, which they tape into their IEJ. (Note: Tape is used when attaching items inside the IEJ because pages often stick together when using glue.)

The Problem Identification Phase concludes with an assignment that will segue students into the Ideation and Research Phases. Individually, either as an in-class or as a homework assignment, students are to review the engineering design challenge taped in their IEJ, paying close attention to the design criteria. From this review they are to add within their IEJ a list of (a) what I know about the problem, a list of (b) what I need to know about the problem, and (c) a sketch of one possible bioreactor system they believe might meet the requirements of the engineering solution. The teacher may choose to provide a handout to structure student responses, or simply give suggestions verbally on how to record the information directly in their journals.

Note that what has been described above is a student-driven approach for crafting an engineering design challenge. A more traditional, teacher-centered approach can be used just as well, especially when time is a factor. Following the attention-gaining event and operationally defining the problem, in the traditional approach the teacher provides her students with an engineering design challenge (design brief) that specifies the context, challenge, and design criteria. In either case, for Problem Scenario (ProbScen) 4A the engineering design challenge would be similar to that shown in Figure 3. Specifically, ProbScen 4A challenges students to design and construct a working prototype of an ethanol bioreactor. The design must be for a continuous flow bioreactor using microorganisms (yeast) immobilized within a biomass solution to reduce product separation costs. The system must provide the optimum internal biological environment and utilize appropriate subsystems for operating and monitoring the bioreactor throughout production.

**(I.) IDEATION** (Criteria, Brainstorm, Generate):

***Criteria/Constraints.*** A successful bioreactor prototype will have an environment ideal for yeast survival and fermentation of sugar. The bioreactor will continuously produce ethanol from a nutrient (sugar) solution, though the actual yield needs to be measured. Construction of the bioreactor prototype will be limited to basic tools and materials.

***Brainstorm.*** To have the greatest surface area available for fermentation, the yeast should probably be in gelatinous balls floating in the sugar solution. Since the NaAlg spheres float just below the surface, a deep unmixed vat of sugar solution would not be very efficient – much of the solution would not come in contact with the yeast. Mixing might help this, but it could damage the spheres and…….

***Known.*** We know that the bioreactor will contain turbo yeast, immobilized in a gelatin-like mixture of calcium chloride and sodium alginate. The bioreaction process will produce $CO_2$. Under room temperature, $CO_2$ is slightly soluble in water. The concentration of sugar solution used is 10%, and the concentration of ethanol produced in this design won't be higher than 18% (or the yeast will stop fermentation), therefore……..

The molar mass molecular elements is: **C** is 12g/mol, **H** is 1g/mol, and **O** is 16g/mol. Under ordinary pressure and room temperature the volume of gas is 22.4L/mol….. Yeast is usually facultative anaerobic and follow both anaerobic and aerobic ways to take energy from sugar and store in ATP temporarily. Yeast do not yield ethanol when $O_2$ is available and only produce ethanol in absence of $O_2$, metabolizing sugar as follow:

$$C_6H_{12}O_6 \xrightarrow{yeast} 2C_2H_5OH + 2CO_2 \uparrow$$

The yeast severs as catalyst-like condition, and is not consumed during the reaction. Since the yeast is an organism, it requires certain environmental conditions to live and be active. Room temperature is good for turbo yeast to fermentation. High pressure may reduce the activity of yeast. The turbo yeast can tolerate at most 18% ethanol. Other organisms, if they exist in the container, may compete with the yeast and produce a harmful product that could impact the fermentation process.

**Figure 4:** Brainstorming what is known.

## What I Know and What I Need to Know

The Ideation and Research phases (DFP: Criteria, Brainstorm, Generate and Explore, Investigate, Examine respectively) have a natural tendency to take place at the same time and, for instructional purposes, are therefore discussed together.

The ideation phase is facilitated as a group activity, with groups of three found to be an ideal number for ensuring both equal voice and maximum engagement by all students. Convergent questioning initiates group ideation by asking students about what they know and need to know concerning the engineering solution. The teacher uses the IEJ as the starting point for soliciting design ideas by first having all groups together review the design challenge taped in their journals. Students share within groups their written responses and sketches they each previously generated for the know/need-to-know assignment. Shared responses about what they know builds the group knowledge base (Fig. 4) while individual sketches (Fig. 5) provide multiple

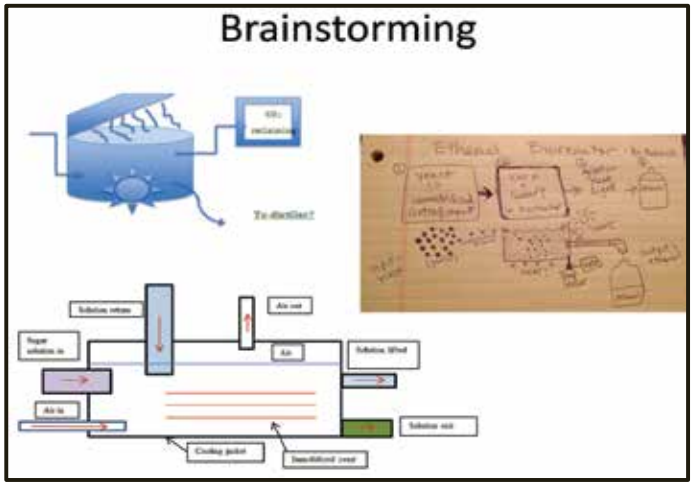


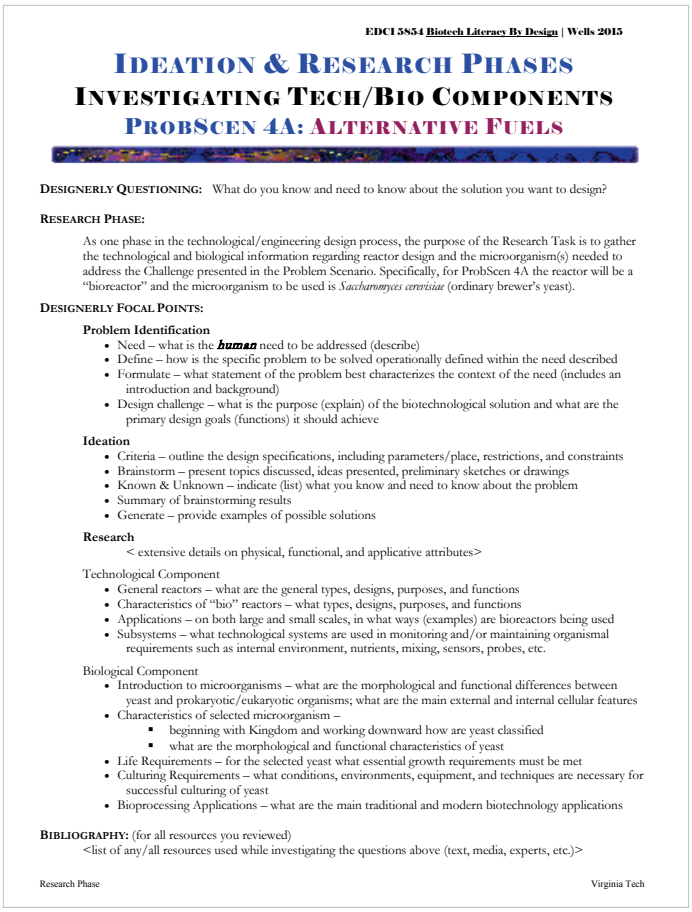

**Figure 5:** Preliminary prototype sketches.

***Unknown.***

- What are the inputs and outputs of the fermentation process? In what amounts?
- What are the densities of sugar water and ethanol? Will they mix evenly, or will one settle out? How do different concentrations of sugar affect this?
- How much ethanol will be produced? What sugar will still remain? How diluted will the ethanol be?
- How can we separate the ethanol from the water? Do we need to evaporate and re-condense the ethanol? *(Note: distillation process not needed for this design challenge.)*
- How long does it take for turbo yeast to change sugar to ethanol?
- What is the best type of sugar? What is the best concentration of sugar?
- What is the optimal temperature for turbo yeast? Are there any other environmental requirements (pH, light, etc.)?
- Is CaAlg gelatin soluble in ethanol or sugar solution?
- Does yeast lose activity after a certain period of anaerobic respiration?
- How do we keep the yeast contacted well with the sugar?

**Figure 6:** Identifying what is NOT known.

design ideas and a number of potential combinations the group can consider. The brainstorming reveals students' resident knowledge regarding the engineering challenge, as well as some potential solution designs. However, at this point groups will still be significantly limited in their ability to decide on a plausible design solution because of what it is they do not know (Fig 6). To move forward, groups will need information specific to the biology and technology inherent within the system to be designed. Instructionally, the Ideation and Research phases present critical opportunities teachers must capitalize on for developing strategies they will use to target and intentionally teach discipline-specific content and practices inherent to the engineering challenge.



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**IDEATION & RESEARCH PHASES**

**INVESTIGATING TECH/BIO COMPONENTS**

**PROBSCEN 4A: ALTERNATIVE FUELS**

**DESIGNERLY QUESTIONING:** What do you know and need to know about the solution you want to design?

**RESEARCH PHASE:**

As one phase in the technological/engineering design process, the purpose of the Research Task is to gather the technological and biological information regarding reactor design and the microorganism(s) needed to address the Challenge presented in the Problem Scenario. Specifically, for ProbScen 4A the reactor will be a "bioreactor" and the microorganism to be used is *Saccharomyces cerevisiae* (ordinary brewer's yeast).

**DESIGNERLY FOCAL POINTS:**

**Problem Identification**

- Need – what is the ***human*** need to be addressed (describe)
- Define – how is the specific problem to be solved operationally defined within the need described
- Formulate – what statement of the problem best characterizes the context of the need (includes an introduction and background)
- Design challenge – what is the purpose (explain) of the biotechnological solution and what are the primary design goals (functions) it should achieve

**Ideation**

- Criteria – outline the design specifications, including parameters/place, restrictions, and constraints
- Brainstorm – present topics discussed, ideas presented, preliminary sketches or drawings
- Known & Unknown – indicate (list) what you know and need to know about the problem
- Summary of brainstorming results
- Generate – provide examples of possible solutions

**Research**

< extensive details on physical, functional, and applicative attributes>

Technological Component

- General reactors – what are the general types, designs, purposes, and functions
- Characteristics of "bio" reactors – what types, designs, purposes, and functions
- Applications – on both large and small scales, in what ways (examples) are bioreactors being used
- Subsystems – what technological systems are used in monitoring and/or maintaining organismal requirements such as internal environment, nutrients, mixing, sensors, probes, etc.

Biological Component

- Introduction to microorganisms – what are the morphological and functional differences between yeast and prokaryotic/eukaryotic organisms; what are the main external and internal cellular features
- Characteristics of selected microorganism –
  - beginning with Kingdom and working downward how are yeast classified
  - what are the morphological and functional characteristics of yeast
- Life Requirements – for the selected yeast what essential growth requirements must be met
- Culturing Requirements – what conditions, environments, equipment, and techniques are necessary for successful culturing of yeast
- Bioprocessing Applications – what are the main traditional and modern biotechnology applications

**BIBLIOGRAPHY:** (for all resources you reviewed)

<list of any/all resources used while investigating the questions above (text, media, experts, etc.)>

Research Phase Virginia Tech

**Figure 7:** 4A Research Task #1.

## Intent to Teach

ProbScen 4A calls for a biotechnical design solution that requires students to consider both the biological and technological aspects in their ideations. Instructionally this is a critical point for ensuring the intentional teaching of targeted content and practices. Specifically, this is where the teacher must recognize and intentionally take advantage of the inherent demands on students to understand the relationships between content and practices required for achieving a successful design solution, which in this case is a continuous flow bioreactor. To do so the teacher will need instructional strategies and tools for guiding students in the types of questions they need to be asking, and in anticipation of those that will be naturally imposed by the solution itself. In ProbScen 4A this is initiated by providing students with a semistructured research task handout (Fig. 7) with questioning prompts that direct students through separate investigations of both the biological and technological components (yeast and bioreactor respectively). The handout is structured around the Designerly Focal Points and begins with prompts that students previously addressed and recorded in their IEJ. Revisiting information in the IEJ stimulates recall of prior learning (Gagne's 3rd Event) and readies students for relating the new information they need to know with what they have already come to know. The handout prompts students to begin recording new entries in their IEJs as they gather information through their investigations of the technological and biological components of the design solution.

Although ProbScen 4A intentionally targets many different discipline-specific learning outcomes (see Figure 1), the examples provided here have been selected to illustrate the intentional teaching of the biology, chemistry, and mathematics required for predicting the gaseous and liquid volumes (predictive analysis) their bioreactor system must accommodate during biomass conversion.

Investigating the capacity of yeast to convert biomass (maize) into ethanol reveals that the bioprocessing of each sugar molecule (dextrose) provides yeast with energy in the form of ATP (Adenosine Triphosphate) they need for cellular respiration, while also producing two molecules of carbon dioxide and two molecules of ethanol as waste products. Students are provided with 10 grams of refined dextrose and distilled water and tasked with making a 10% solution (Fig. 8) to serve as the biomass solution for use in their bioreactors. Dextrose, the D-form of glucose, is made up of carbon, hydrogen, and oxygen ($C_6H_{12}O_6$) that when bioprocessed by yeast is converted to carbon dioxide ($CO_2$) and

## Conversions & Calculations Refresher

Yeast will convert 1 molecule of sugar (dextrose) to 2 molecules of carbon dioxide and 2 of ethanol

($1\ C_6H_{12}O_6 \rightarrow 2\ CO_2 + 2\ EtOH$)

Sugar = dextrose = $C_6H_{12}O_6$

Molecular weight = 6(atomic mass of C) +12(atomic mass of H) +6(atomic weight of O)

=6(12) + 12(1) + 6(16)

=180g/mole

| Hydrogen 1 | Carbon 6 | Oxygen 8 |
|---|---|---|
| H | C | O |
| 1.00794 | 12.011 | 15.9994 |

Percent composition by mass = mass solute/mass of the solvent

Water = 1g = 1mL= $1cm^3$

10% solution = $\left(\frac{100g\ sugar}{X\ grams\ water}\right) \times 100\%$

X=1000g $H_2O$ = 1000mL $H_2O$

10% solution = $\left(\frac{10g\ sugar}{X\ grams\ water}\right) \times 100\%$

X=100g $H_2O$ = 100mL $H_2O$

**Figure 8:** Calculating percent solution.

ethanol ($CH_3CH_2OH$) in equal parts. At this point most students are sure to need a little help in refreshing their memories[3] about chemistry in order to work the calculations needed for preparing a 10% solution and for predicting the maximum possible amount (volume) of both carbon dioxide and ethanol from the 10 grams of dextrose. A quick review of the periodic table reminds students that this is where they find the molecular weight of carbon, hydrogen, and oxygen needed in their calculations (Fig. 9). Using this information they can calculate the maximum possible volume for both carbon dioxide and ethanol that can be produced from 10 grams of dextrose, given the volume of one mole of a gas at standard temperature and pressure is 22.7 liters and will have a density of 1.25 grams per liter (Fig. 10). The predicted volumes provide students with the information they need for determining the minimum size for a bioreactor that could accommodate the maximum possible volume of ethanol produced. This information is also used when designing any structures external to the reactor vessel students might decide they need in capturing the carbon dioxide produced. These and other necessary calculations provide students with the baseline data they need to make informed decisions when selecting the most promising of their alternative bioreactor designs. Immersing students in this authentic use of content and practice is intentional on the part of the teacher for achieving targeted grade level mathematics and chemistry learning outcomes.

Based on their calculations for predicted performance, students select their best potential prototype designs. Once selected, key design concepts within each potential prototype need to be evaluated (tested and analyzed) against the criteria stated in the design challenge. Evaluation is accomplished by conducting actual trials on various system components. Data from these trials must be collected, analyzed, and then interpreted to determine which combination of components provides the optimum fit for addressing the problem. At this point a quick review of the design challenge criteria from the Problem Identification phase reminds students that a successful bioreactor is one that yields the highest possible volume of ethanol. Given that the bioprocessing of dextrose produces equal parts carbon dioxide and ethanol, they can determine the efficiency of their prototype by measuring the volume of either byproduct produced. However, students soon realize there are challenges associated with measuring gas and/or liquid volumes in situ; i.e., within the actual system (Fig. 11). Regardless of which byproduct they choose to measure, when conducting their trials, data are collected, carefully recorded, analyzed, and then findings interpreted. This scientific experimentation requires students to plan out an experimental design, identify what data will be collected (observational, numerical, etc.), and based on findings, decide which volume to measure as well as where and how they will measure it (Fig. 12). These science practices are all intentionally targeted as learning outcomes by the teacher during his or her design of instruction.

Closer inspection of the element **"Carbon"** – revisiting **atomic properties**

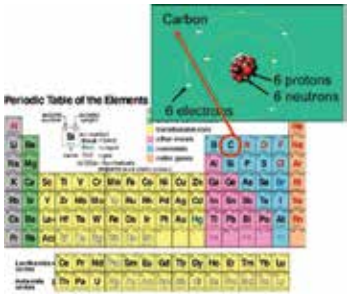



**Figure 9:** Locating Molecular Weights.

[3]The content knowledge required for teachers to facilitate this level of predictive analysis is what they were exposed to in 10th grade biology and chemistry. Or refresh by collaborating with STEM colleagues!

Volume (in liters) of **carbon dioxide *gas*** produced:

10g dextrose = $\left(\frac{?\ mole}{?\ g}\right)$ = 0.? moles dextrose

0.? moles dextrose = $\left(\frac{2\ moles\ CO_2}{1\ mole\ dextrose}\right)$ = 0.? moles $CO_2$

0.? moles $CO_2$ = $\left(\frac{22.4\ L\ @STP}{1\ mole\ gas}\right)$ = ? L $CO_2$

**Figure 10:** Calculating $CO_2$ Volume.

The yield is almost one and a half times the predicted amount. Using mass to calculate volume, while theoretically possible, is practically inaccurate due to the trapped water in the beads and possibly the collected liquid was not drained with a fine enough strainer, thus leaving a fine suspension of yeast/gel in the resulting liquid. Thus the yield is too high in the calculations. This analysis was proven correct when the process was repeated without the immobilization of yeast and measuring the entire weight.

**Figure 11:** Theoretical vs. actual calculations.

Results from the Solution Evaluation phase bring to light both strengths and weaknesses in the prototype components tested. Students use this information to make prototype alterations that will capitalize on the strengths of individual components or lead to improvements in the weak areas of their design. The redesigned prototype undergoes experimental testing again, with results used to determine what additional refinements may still be necessary. This iterative process is another practice the teacher intentionally targets as a learning outcome specifically addressing the technology and engineering disciplines.

As highlighted multiple times in previous sections, the success of a teacher's intent to teach the content and practice of different disciplines—and evidence of students having learned it—can be assessed formatively at many points throughout the PIRPOSAL phases of design. From both the teacher and student perspectives, summative assessment during the Learned Outcomes phase occurs using various modes of communication—written, verbal, graphically, etc. Regardless of mode, the ultimate learning outcome students should be able to demonstrate following T/E DBL is that of understanding—an ability to demonstrate their schematic and strategic higher-order thinking skills. When a student, or group of students, is asked to describe the features and attributes of the components that were chosen for their final prototype, they are primarily demonstrating declarative knowledge (*knowing that*). In explaining how they investigated, designed, prototyped, and tested their bioreactor, they are demonstrating their procedural knowledge (*knowing how*). But when explaining the various relationships between biological and technological elements of their prototype, the reason cellular respiration results in a useful biofuel byproduct, or why calculating liquid and gaseous volumes informs them of prototype requirements, they are demonstrating conceptual understanding (*knowing why, when, and where to use knowledge*)—all of which are characteristics reflective of true higher-order thinking abilities (Wells, 2010, p. 199).

In the context of T/E design-based learning, the ability of students to demonstrate conceptual knowledge and deep understanding as a result of their engagement in engineering design is a primary instructional goal. Students are well practiced in being able to tell what they know (declarative) and recounting the steps they followed (procedural) in completing a design challenge. However, to ensure students will communicate conceptual knowledge and demonstrate understandings, teachers will want to structure the Learned Outcomes phase in a way that presents students with key questions to guide their discussion. For example, posing questions regarding their design iterations can reveal students' transitions from convergent to divergent thinking as they progressed from lower-order questions into the deeper reasoning ones—from knowledge domain to concept domain. And posing questions that ask students to explain how recognizing connections between STEM content and

## Solution Evaluation-Melissa

| TIME [Minutes & Hours] | MEASUREMENTS Balloon Circumference | Room Temperature | OBSERVATIONS |
|---|---|---|---|
| 9:31 PM | 0 inches | 75°F | Balloon sucked inward, Immobilized yeast cells are mixed within the sugar solution, and a distinct odor that is coming from the yeast. [See Picture 1 & 2.] |
| 10:01 PM | 0 inches | 75°F | Balloon is starting to puff out [see Picture 3.], Immobilized yeast cells are floating on top of sugar solution, the sugar solution appears to have a dark color, and condensation has begun to develop on the Erlenmeyer flask. |
| 10:31 PM | 1 inch | 75°F | The balloon appears to be "lifting" off with (what is assumed to be) Carbon Dioxide- $CO_2$ [see Picture 4.] |
| 11:01 PM | 6 inches | 76°F | Balloon is growing, large bubbles are mixed within the immobilized yeast cells and sugar solution, and small bubbles are blanketing the top of the yeast [see Picture 5.] |
| 11:31 PM | 6.5 inches | 75°F | Balloon continues to grow, milk jug container has "puffed" out its sides, not as many large bubbles mixed in with the sugar solution [see Picture 6.] |

**Figure 12:** Table of recorded trial data.

practices allowed them to make informed designerly decisions demonstrates the reasoning used in justifying their choices in prototype design. These explanations reflect students' designerly ways of knowing and their development of *integrative STEM habits of mind*—that unique amalgam of all disciplinary-specific habits of mind essential for responding to the demands imposed on the learner when engaged in engineering design.

Reflected in the eight phases of the PIRPOSAL model is the centrality of questioning as a primary instructional strategy for intentionally and concurrently teaching STEM content and practices. Intentionality is a hallmark of the I-STEM ED approach and embodies the unique potential of T/E design-based learning as delivered through technology and engineering education. The DBBL exemplar presented in this article afforded the opportunity for illustrating the intentional teaching of a select few targeted learning outcomes. Unfortunately, doing so for the full cadre of STEM learning outcomes that are targeted when teaching ProbScen 4A is not possible within the limited space for this article. Nor is there space to discuss the details of all instructional strategies used in teaching those outcomes. However, anyone wishing to delve more deeply into using the PIRPOSAL model for teaching I-STEM ED and DBBL should contact the author regarding opportunities for participating in these on-campus and distance graduate courses.

## Broad Applicability

ProbScen 4A is only one of more than 40 Problem Scenarios included in the Design Based Biotechnology Literacy Teaching Guide, and biotechnology is but one of many content areas addressed in *Standards for Technological Literacy* (ITEA/ITEEA, 2000, 2002, 2007) in technology and engineering education. Within each of these content areas, the PIRPOSAL model meets the criteria for implementing I-STEM ED by using technological/engineering design-based learning as the pedagogical vehicle to promote students' higher-order thinking. There is a growing body of evidence supporting I-STEM ED as a viable approach for promoting this level of thinking, not only in technology and engineering education, but in the other STEM disciplines as well (Wells, 2016b).

Although the PIRPOSAL model shows promise for supporting I-STEM ED as a viable and defensible approach for developing students with 21st century thinking abilities, conceptually it is not yet part of mainstream educational reform. The challenge in systemically achieving this type of "reformed education" is getting key stakeholders such as national STEM education organizations, curriculum designers, and classroom teachers to recognize the potential of T/E DBL as a viable I-STEM ED approach—one that is explicit in its pedagogical goal of having students *Design to Understand* (D2U).

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