Problem-based Learning

Design-based Learning for Biology

GENETIC ENGINEERING EXPERIENCE IMPROVES UNDERSTANDING OF GENE EXPRESSION

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Gene expression is a difficult topic for students to learn and comprehend, at least partially because it involves various biochemical structures and processes occurring at the microscopic level. Designer Bacteria, a design-based learning (DBL) unit for high-school students, applies principles of DBL to the teaching of gene expression. Throughout the 8-week unit, students genetically engineer bacteria to meet a need in their own lives. Through a series of investigations, discussions, and design modifications, students learn about the molecular processes and structures involved in gene expression, and how these processes and structures are dependent upon various environmental variables. This article is intended to describe the Designer Bacteria unit and report preliminary results of student progress and performance on pre-unit and post-unit assessments. Teacher experiences and student progress indicate that Designer Bacteria successfully taught core aspects of gene expression through DBL.

Keywords: Gene expression, design-based learning, high-school biology, bacteria.

Ask many adults about their high-school science experience and they will say things like "boring," "terrible," or "overwhelming." Current efforts in educational reform are attempting to change that perception for today's high-school student. Government mandates for accountability in high-school science have required educators and administrators to evaluate the effectiveness of their current science curricula. It is now clear that common contemporary approaches are insufficient to make progress in high-school science achievement. Students are not prepared to meet government standards and even less prepared to pursue careers in science, with an incredibly low number of students entering scientific fields [1]. This article describes one approach to improving student achievement and interest in the biological sciences.

Biology is a science course that is required for high-school graduation. Recent reviews of high-school biology textbooks indicate that they inadequately cover the core content and frequently contain erroneous details [2]. Contemporary textbooks include a large number of topics and concepts but the depth of coverage for each concept is low. As a result, there are a large number of heavy textbooks wrought with numerous disconnected scientific facts and activities, making it difficult for students to develop meaningful understanding of the science [3]. The byproduct of these changes is a lack of scientific understanding, decreased student interest, and subsequently, low attainment scores. According to the 2005 Nation's Report card, only 20% of U.S. high-school students achieved proficient scores, 54% achieved basic scores, and 26% of U.S. high-school students fail to attain even a basic level of science proficiency [4]. Distressingly, the 2005 proficiency scores were significantly lower than the proficiency scores reported in 1996.

Design-based learning (DBL),[1] where students learn content while designing an object or prototype, has the potential to dramatically increase student learning by incorporating design experiences with the science. DBL is a type of problem-based learning (PBL), in which students work together in teams to solve a problem. This type of instruction encourages students to learn information in a more meaningful way. Numerous studies have documented the success of PBL approaches across the curriculum more broadly [e.g., 5], and in science education more specifically [e.g., 6]. DBL is slightly more specific than PBL because students work together specifically to create or design a new invention/prototype.

Interest has been increasing in the inclusion of DBL in the curriculum [e.g., 7, 8], inspiring the development of successful design-based units for school science [9–13]. Successful DBL units increase student interest and motivation, producing increased performance. Outside of university engineering science courses, it is relatively rare for design to be included in science courses [14]. Very few DBL curricula have been developed or implemented for high-school science [9, 13, 15] and, currently, no published DBL curricula exist for high-school biology.

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[1]The abbreviations used are: DBL, design-based learning; PBL, problem-based learning; LB, Luria broth.

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The goal of this article is to describe the details of a DBL unit for high-school biology courses that is focused on the content area of gene expression. First, the article describes why the topic of gene expression is well suited for an enrichment approach like DBL. Next, the article explains the structure of an 8-week DBL unit, Designer Bacteria, implemented in urban and rural high schools. The Designer Bacteria unit challenges students to genetically modify bacteria so they are able to express new traits that can be used to improve students' lives. The explanation of the unit includes two interleaved storylines. The Design Storyline details how the students work through improvements on their prototypes during the unit. The Gene Expression Storyline details the parallel progression of science concepts and identifies how knowledge about gene expression is acquired and used to improve the students' prototypes. Following the description of the two storylines, additional features integral to the unit are explained. Finally, assessment data are presented as evidence for the success of the unit.

GENE EXPRESSION AS AN APPROPRIATE DBL SUBJECT

Widespread implementation of DBL units depends upon choosing good conceptual targets. Specifically, the targets should meet four fundamental criteria: 1) central to the field of biology, 2) difficult to teach and learn, 3) building block of the larger biology curriculum, and 4) significant importance for the mandated biology curriculum at the state and national levels. Targets meeting all four of these criteria are ones that teachers realize they need to teach well but are not ones that students are mastering currently. The section that follows briefly summarizes why gene expression meets those criteria.

First, genetics is central to a modern understanding of most biological concepts. Because gene expression is so fundamental to the field, it is included in most high-school biology textbooks and all university introductory biology, biochemistry, and microbiology textbooks.

Second, various assessments of high-school students' understanding and knowledge indicate that the topic of gene expression is difficult to teach and that current attainment is low, with an amazing 65% of students having an unsatisfactory understanding of gene expression in one recent national assessment [16]. The speed at which molecular biology advances has left large gaps between teachers' understanding and the current state of scientific thinking [17]. As a consequence, teachers may be more inclined to instruct students through simple memorization of various biological concepts [18]. In addition to these knowledge gaps, the concepts involved in the topic of gene expression are difficult to learn because students need to acquire and integrate knowledge of complex structures (e.g., cellular organelles, proteins, nucleic acids) to conceptualize the complex biological mechanisms of transcription and translation. Furthermore, because most of these mechanisms are unobservable, it is difficult for students to develop a solid understanding of how cells express traits [19–21].

Third, a solid understanding of gene expression, especially at the molecular level could be used as leverage for other topics in the biology curriculum. Information gained on how cells express traits provides better opportunities for students to understand cell theory, evolution/adaptation, ecology, biochemistry, and ethics. For example, if students learn about gene expression before learning cell theory, then they will have experience with various cellular structures and processes fundamental to understanding cell theory. These structures and processes could include, but are not limited to, cell membranes, nucleus or nucleiod region, ribosomes, cytoplasm, cell division, and the cell cycle.

Fourth, some version of genetics has been a part of the required curriculum from the second half of the 20th century onwards. More recently, high-school science standards have mandated teaching gene expression from a molecular perspective [e.g., 22]. Many experienced teachers' knowledge of these advanced techniques is outdated because of the vast amount of progress in gene expression during the last few years. For example, teachers who completed their undergraduate education more than 20 years ago would have little experience with the technological advancements in gene sequencing or recombinant DNA manipulations; areas that have become central to the study of gene expression since that time. For this reason, they might be especially interested in opportunities that will enhance their own skills and understanding about molecular biology; the teacher workshops provided with the Designer Bacteria unit are such an opportunity.

Gene Expression Topics

Many topics are related to a solid understanding of molecular gene expression. From such a broader list of topics, a smaller focal set was selected that included only those topics that are most important for high-school biology courses. These selected topics included: genes, heredity, DNA structure, cell division, and replication. In addition to these essential ideas, additional topics were included so that students might reach a deeper understanding of gene expression on a molecular level, in order that they would have a solid causal model that they could use to understand the various big ideas. Causal models are important for enabling students to go beyond memorization [23–25]. These more detailed topics included mRNA and transcription, tRNA and translation, codons, amino acids, and gene products (proteins).[2] Based on these selected topics, the learning goals of the unit were that students would be able to: 1) realize that genes are made of DNA, 2) recognize that genes are inherited from previous generations, 3) identify the structure and parts of DNA, 4) understand the process of DNA replication for cell division, and 5) model the flow of information from DNA to RNA to protein through transcription and translation.

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[2]Scientific explanation of these phenomena would include promoters. Because this topic is not included in most high-school science standards [e.g., 22], high-school biology teacher consultants requested that it be excluded from the curriculum. Any adaptations of this unit to the collegiate level should be modified to include promoters.

DESIGNER BACTERIA: OVERALL UNIT STRUCTURE

DBL can vary in structure from extremely open (e.g., "Go make an X at home") to entirely scripted (e.g., "Step 1: Open the kit ..."). The open structure provides too little guidance for what methods might be fruitful for solving the problem. In this case, students waste too much time spinning their wheels and rarely find closure to the problem [26–28]. The entirely scripted approach removes all the thinking [24, 29]. This unit has an intermediate structure that has been carefully created to include several layers. These layers leave enough decisions in the hands of the students, requiring careful thought about science content. In addition, the unit contains sufficient structure so that students have clear starting points and methods for directing their progress towards conceptually rich data.

The unit followed Edelson and Reiser's [30] four strategies to improve the inclusion of authentic practice in school curricula. First, the context must be meaningful for the students. Second, the complexity of the methodology and techniques used by highly trained scientists must be reduced for the students. Third, implicit practices of the science must be made explicit to the students. Fourth, activities must be strategically sequenced to bridge the gap between students' existing knowledge and the to-be-learned content.

The task of genetically modifying bacteria with new DNA to display new traits provided opportunities for students to engage meaningfully with the content of gene expression. Where appropriate, sophisticated techniques were simplified so that students had the opportunity to genetically engineer their prototype themselves. This strategy allowed students to take ownership of their prototype while gaining confidence about numerous techniques and strategically utilizing classroom time to think deeply about biological ideas rather than just techniques. Small group discussions, class discussions and other ritualized activities provided opportunities for students to explore relevant scientific practices explicitly. For example, students brainstormed how they could conduct new experiments that might give them information about how to improve their prototype, conducted those experiments, and discussed their results in ways similar to the scientific community. Students' initial hypotheses were not especially sophisticated, but became more sophisticated with each new experiment based on the results of their prior experiments and their discussions about these results. Teachers used various moments within these experiences to make the reasons for certain scientific practices explicit. For example, discussions about experimental designs and results were used to highlight the necessity of experimental controls or to improve the hypothesis quality.

The Designer Bacteria incorporated these authentic practices via two main storylines: design and gene expression. These storylines cover three main groups of activities: prototype design, prototype development, and prototype debut (see Figure 1).

Design Storyline

The unit provides students with experiences where biochemistry and molecular biology intersect with engi-
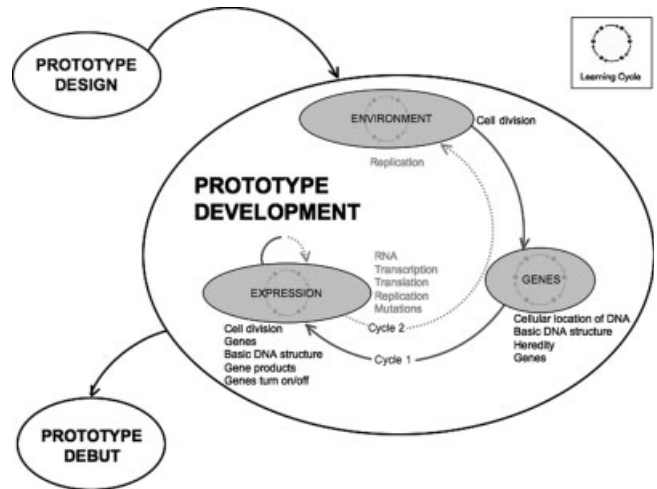

Fɪɢ. 1. **The Designer Bacteria unit interleaves science and design practices with the topic of gene expression.**

neering and design, enabling students to see how creativity and scientific knowledge are important components of developing new prototypes that will improve their everyday lives. Similar to scientists and engineers, students developed their designs in small teams typically consisting of four students. The team structure allowed students to explore a greater depth of ideas and design alternatives. Teams kept track of their progress using a team guide, similar to the records engineers and scientists keep about their own progress.

The use of regulary rotating student roles facilitates group learning [31, 32]. For this reason, four roles were created. The Lead Biologist supervised teamwork, led the lab procedures, and kept other members on task. The Analytical Biologist obtained the team guide from the classroom bookcase, recorded the procedures, and completed the team guide based on the team's work. The General Biologist obtained all necessary supplies for the investigations and assisted the Lead Biologist during the lab work. The Quality Assurance Biologist ensured that the lab space was cleaned before and after lab investigations, and rated each team member's participation on the day's tasks.

Students begin the unit thinking about how genetic engineering has been used to meet needs and improve lives in Prototype Design. After an exposure to some examples of how bacteria have been used in the past to improve human lives, the students think about how they could modify bacteria to create a prototype that meets a need that they have in their own lives. Next, students consider what specifications their prototype must have to be able to function and what specifications are nice-to-have and might make their prototype more appealing. Students presented their initial ideas and received feedback from their classmates and teachers during Mini-Symposium I, simulating the way that engineers and scientists receive feedback.

During the Prototype Development, students think about how they could break down their problem into solvable parts, i.e., system decomposition. Students' prototypes comprised three subsystems: Environment,
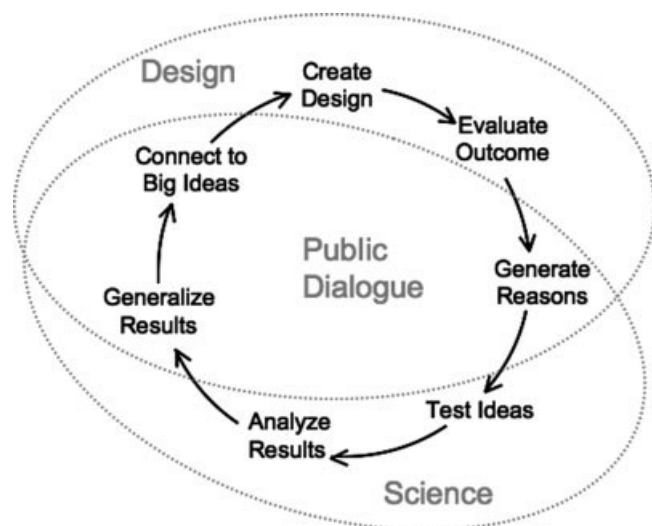
about experiments, design successes and failures, scientific knowledge and present one best prototype.

Gene Expression Storyline

Students worked their way through the Gene Expression Storyline following the Learning Cycle in each of the three prototype subsystems mentioned earlier: Environment, Genes, and Expression.

Environment Subsystem—The Environment Subsystem allowed students to investigate the conditions that are favorable for bacterial growth and replication and focused on three big ideas:

1) To optimize cell division, the bacteria must be grown under the proper conditions.
2) For the cells to divide and the colony to grow, the DNA in each parent cell must be replicated and a copy given to each daughter cell.
3) Mutations are mistakes in the DNA sequence that result in an incorrect protein blueprint and a range of cellular effects.

Because of limitations of cost and robustness, students were limited to only two strains of bacteria: *E. coli* DH5-α and XL1blue. Initially, students attempted to get one of these two strains of bacteria to grow on a plate of agar. Students used the dilution streak method to inoculate an agar plate chosen from among five alternatives: nutrient agar, Luria broth (LB), potato dextrose, LB with ampicillin (LB-amp), Mackonkey, LB with Xgal (LB-Xgal), or LB-Xgal and ampicillin (LB-Xgal-Amp). At this point, students did not know how the bacteria would grow on these plates or how these plates differed from one another. After an initial incubation period, students evaluated their outcomes and discussed their results. Students created several tests that systematically manipulated several environmental factors like temperature, available chemicals/nutrients, and incubation time and decided that the dependent measure of these experiments was the growth of bacteria. Based on the results, students considered how the nutrients, or chemicals in the agar constrained cell division and saw first-hand that bacterial cells do not divide or reproduce without the appropriate nutrients in the environment, the growth of a bacterial colony is dependent on the rate of cell division, and various environmental factors can slow down or speed up bacterial growth.

In addition, the students chose to investigate the differences between small and large bacterial colonies. Some students were not sure whether larger colonies contained more bacteria or bigger bacterial cells. After creating their own wet mount slides, students saw that increased bacterial colony size was a result of more cells not bigger cells.

Near the end of the unit, again students considered the role of the environment for revising their prototype so that it functions according to their specifications. Most importantly, students needed to consider how the bacteria that they used in their initial prototype may or may not be appropriate for their final prototype. Where *E. coli*

Fɪɢ. 2. **The Learning Cycle structures learning for students as they move through each of the Designer Bacteria subsystems.**

Genes, and Expression (see Figure 1). Students cycled through each of these subsystems once and revisited the Expression and Environment subsystems. From a pure design perspective, the number of cycles through each subsystem is arbitrary. This particular number was chosen because of the depth of biology concepts that needed to be taught in the overall unit and how subsystems connected to specific biology concepts.

A sequence of ritualized activities, repeated during each subsystem, made explicit connections to scientific knowledge and enabled efficient prototype improvements, make up the Learning Cycle (see Figure 2). Results from previous DBL units indicate that teachers and students need ritualized activities to guide them through the design process [9, 10]. Without this basic structure, students and teachers feel that they are fumbling around in their designs and they are not consistently exposed to the scientific knowledge necessary to improve their design and to meet the science goals. At Create Design, students developed a design idea and tried it out. During Evaluate Outcomes, students measured the success of their design. For various reasons, these initial designs tended to fail. Reasons for the outcomes and possible ways to test those reasons were discussed as a class during Generate Reasons. From the Generate Reasons node, students entered the science space while they executed their proposed tests during Test Ideas. Students analyzed the results from their experiments in Analyze Results. They discussed these results during Generalize Results to uncover a pattern, theory, or trend. Finally, in Connect to Big Ideas students linked their prototype to key science concept(s).

During the Prototype Debut, students prepared a patent application. This application was not as extensive as a real application, but it did give students the opportunity to describe the scope and function of their design in written form. Finally, students prepared posters and completed a Gallery Walk, similar to Kolodner *et al.* [10]. The Gallery Walk simulates a science fair where students talk

are inappropriate, students needed to offer suggestions of more appropriate bacteria. For example, one group of students created a prototype that would express a blue color on black ice. After learning that *E. coli* do not colonize efficiently at temperatures below freezing, they needed to find another bacteria. Reconsideration of how the environment and DNA interact gave students the opportunity to consider that these interactions might result in changes to the DNA, and that these changes can be passed on to subsequent generations via DNA replication and cell division.

Genes Subsystem—After students grew bacteria successfully on an agar plate, they considered how they might get the bacteria to exhibit new traits during the Genes Subsystem. Students had the opportunity to introduce new genes, via plasmids, using a basic bacterial transformation procedure that caused the bacteria to express new traits while focusing on two big ideas:

1) DNA is a double-stranded, antiparallel molecule located in the bacterial cytoplasm that codes for genes.
2) Genes are inherited from previous generations and transmit a characteristic.

Students inserted the plasmids using standard bacterial transformation techniques. Due to cost and robustness limitations, students were limited to two plasmids: pGreen and pBLU® [33], both available through Carolina Biological Supply Company. To test the success of their bacteria transformations, students compared the bacterial growth after overnight incubation on four agar plates. Following standard protocols both experimental (i.e., transformed with the new plasmid) and control (i.e., transformed solution without the new plasmid) solutions were each placed on two separate agar plates: one with LB nutrients (LB) and one with LB nutrients plus ampicillin (LB/Amp).

On average, only one or two teams in each class successfully transformed the bacteria on their first try. Students created additional tests that might increase their likelihood of transformation success. Because of their previous experiences discussing the environment, many students manipulated various environmental factors, like temperature, nutrients, or incubation time. Some students ran the transformation procedures again paying very careful attention to their technique. Other students believed that the best way to get their bacteria to express a color or begin to glow would be to add some sort of luminescent material, dye or food coloring to the bacterial colony. However, these students found that environmental manipulations like the insertion of dyes did not cause the trait to carry into the next generation.

In addition, students created a representation of part of the DNA for the bacteria that they were using in their prototype using simple three-dimensional DNA models. They practiced assembling complementary DNA strands and modeled the process that cells go through during DNA replication and cell division, exposing them to the physical properties of DNA, its nucleotides, the complementary base-pairing of nucleotides, hydrogen bonding, the unzipping and replication of DNA, transcription of DNA into mRNA, translation of mRNA into protein on a ribosome via tRNA, and the assembly of amino acids forming a protein chain.

Expression Subsystem—Students realized that inserting new plasmids was not enough to meet all of their prototype requirements and used the Expression Subsystem to learn more about how cells get their traits from DNA by focusing on three big ideas:

1) Genes can be turned on and off, depending on the environment, to produce gene products (proteins) that give rise to a characteristic.
2) The cell uses DNA as the blueprint for the proteins that give rise to a characteristic or trait.
3) To make protein, the cell transcribes a gene from the DNA into RNA and translates that RNA into the needed protein.

By this time, students noticed that the color of their successfully transformed bacteria had begun to fade. Students decided that they should try to inoculate those bacteria onto a fresh agar plate to see if the bacteria would express the color again. Even though the bacteria expressed a brighter color after the inoculation, the color was not bright enough to meet their specifications. Students wondered if there was a way to increase the amount of nutrients or provide more effective nutrients to the bacteria so that they would express more of the desired trait. Students spread one of six nutrient enhancement solutions, tetradecanol at 0.2, 0.3, and 0.4 M concentrations or *N*-(B-ketocaproyl)-DL-homoserine lactone at 0.2, 0.3, and 0.4 M concentrations, onto an agar plate, let the plate dry, and inoculated the plate with their transformed bacteria. Students found that the nutrient enhancement solutions allowed their bacteria to express more of the trait. However, the students were unsure why. To figure that out, they had to learn about transcription and translation.

Students used the DNA models to simulate the process of transcribing DNA into mRNA and translating mRNA into amino acids that combine to form a protein chain, illustrating that the phenotypic trait is caused by the protein produced by the expression of one or more genes. After learning about the processes of transcription and translation, students interpreted (fictitious) data collected using sophisticated enhancement solutions to explore further what might happen in the cell if transcription and/or translation were enhanced. This complex reasoning task required students to think deeply about how enhancement of one or both of these processes would influence DNA, RNA, and protein concentrations in the cell and how the enhancement of one trait might result inadvertently in the enhancement of other, sometimes undesirable, traits.

ADDITIONAL FEATURES

Additional features are necessary to encourage widespread implementation of this DBL unit. First, the unit needs to be relevant to students, increase student interest and motivation, and indirectly motivate teachers to continue implementing the unit. In this unit, the key feature that created personal relevance was that students were asked to design bacteria that would meet a need in their own lives. Example student prototypes included a

tanning lotion containing bacteria that turn blue when the skin is about to burn, bacteria that fluoresce unless the soil they grow in does not contain the right chemicals to grow plants, diapers that contain bacteria that turn blue when wet, bacteria that turn blue when black ice accumulates, or bacteria that turn blue when the water in a fish tank needs to be changed. Teachers reported that their students were very motivated and interested in the unit. For example, one teacher said

> I found that because it was their own idea, that they really wanted to make it work, so they put a little bit more effort into it.... if their bacteria did not turn blue, then they wanted to know why and what they could do to change that.

Another teacher said "The students had a say-so in things. I directed the unit, but they had an input into their project. They liked that."

Second, the unit needs to be inexpensive so that the target audience (i.e., teachers and students from urban and rural districts) can sustain it. The current unit costs less than $10 per student during the first implementation and about $7 per student to refurbish materials during subsequent years. These materials are used to give students authentic experiences for about 7 weeks. By contrast, contemporary machines and supplies for gene sequencing cost at least $50,000 to supply a typical classroom! Alternatively, if teachers tried just one experiment from this unit using a commercial kit, then it would cost an average of $4 per student for just one lab activity.

Third, the design-task needs to be relevant directly to the biology concepts that were targeted for instruction. Design tasks that are too easy do not motivate students to investigate further because they are satisfied with the product. Students who reached only partial success with a design were motivated to continue their investigations of the phenomena. But, too little success can demotivate students.

EVIDENCE OF DESIGNER BACTERIA SUCCESS

It was a goal of this unit to improve higher level reasoning of gene expression topics, rather than mere memorization of specific terms and processes. Short-answer essay questions on gene expression available from the sample question database of the NAEP (National Assessment of Educational Progress) [16] were selected to test higher-level reasoning. Together these eight questions assessed both conceptual understanding and practical reasoning about gene expression. NAEP classifies these questions as difficult for 12th grade students [16]; it is necessary to have a rather complete understanding and sophisticated reasoning about a specific process to receive the high scores. These questions were appropriate because they addressed the major content areas of unit and the high-school content standards relevant to the topic [22].

During the first year of implementation, over 500 urban and rural high-school students participated in the unit. For purposes of detailed evaluation, a sample of 89 students was asked to complete the NAEP questions. The NAEP questions were divided into three forms, with three NAEP questions on each pretest form and four NAEP questions on each posttest form. The selected sample had similar demographics with the NAEP public school sample.

As this was the first evaluation of the unit, it was determined that this was a suitable way to evaluate this first implementation of the unit because the students in the unit and the students in the national sample would have completed this material in their coursework. At some level, using this comparison might reduce the apparent effectiveness of the unit as many students in the national sample may have had more biology experience and more experience than the current sample with the topic area through supplemental biology coursework because the current sample included only students completing the first half of their first year of high-school biology. Furthermore, the questions do not match exactly the content of the Designer Bacteria unit. Comparisons were made between the students who completed the unit and the national sample to see whether any understanding the students gained during the unit was flexible enough to be applied to relevant, but not exact situations because this sort of flexibility, also called transfer, is difficult for students [e.g., 34]. Progress on the NAEP questions would indicate that students had learned not only the content information presented in the unit, but that they had the ability to apply what they know to new situations as well.

Responses for all questions were scored using the NAEP criteria for blank, off-task, unsatisfactory, partial, and complete responses [16]. The data were subjected to one-way repeated measures analyses of variance, with session as a factor (pre-unit *vs.* post-unit). Cohen's *d* [35] was used to calculate effect sizes (difference in means divided by standard deviation of the pre-unit data; small ≤ 0.2; medium $= 0.5$; large ≥ 0.8).

During the pre-unit assessment an overwhelming proportion of students left the response section blank ($M_{pre-unit} = 0.56$), no students gave responses classified as off-task. Some students did give responses that were relevant to the question. These responses were classified as unsatisfactory ($M_{pre-unit} = 0.25$) or partial ($M_{pre-unit} = 0.19$). No students provided responses that could be classified as complete: Students knew very little about the topic before the unit.

The large number of blank responses dropped dramatically by the posttest ($M_{post-unit} = 0.07$, $F(1,88) = 324.34$, $p < 0.0001$, $d = 1.26$). Again, no students gave off-task responses. As the number of blank responses decreased, the number of actual responses increased for the other categories. The proportion of unsatisfactory responses increased compared to the pre-unit assessments ($M_{post-unit} = 0.39$, $F(1,88) = 15.11$, $p < 0.0001$, $d = 0.30$). However, this number is substantially below the national average of 0.57 for public school students. In contrast, the proportion of partial responses was significantly higher than during the pre-unit assessment ($M_{post-unit} = 0.48$, $F(1,88) = 65.34$, $p < 0.0001$, $d = 0.65$), and substantially higher than the national average of 0.32. Finally, the proportion of complete responses increased significantly between the pre-unit and post-unit assessments ($M_{post-unit} = 0.06$, $F(1,88) = 18.93$, $p < 0.0001$, $d = 0.37$), with the post-unit rate comparable to the national average of 0.06 for public school students.

The increased performance between pre-unit and post-unit on this difficult assessment indicated that the students had gained a good understanding of genetics and gene expression during this unit. Furthermore, because the article and questions were not tied directly to the exact content of the unit, students displayed a good ability to transfer what they had learned to new situations. These performance gains are impressive, particularly because of the difficult nature of the questions and scoring rubric.

These results, classroom observations, and teacher comments indicated that during the unit students were able to: 1) realize that genes are made of DNA, 2) recognize that genes are inherited from previous generations, 3) identify the structure and parts of DNA, 4) understand the process of replication for cell division, and 5) model the flow of information from DNA to RNA to protein through transcription and translation.

CONCLUSION

This article described one curriculum, Designer Bacteria, that successfully applied DBL to gene expression. Gene expression is suitable for DBL because it is central to the field of biology, difficult to learn, a building block of the larger biology curriculum, and significant to the mandated high-school curriculum at the national and state level. The Designer Bacteria unit utilized strategically structured design activities where students genetically modified bacteria to express new traits using authentic scientific practices. The unit included additional features to increase widespread implementation. These features included student relevance, controlled costs, strategically selected student materials, and improved science outcomes.

This work provides evidence that DBL can be an effective tool for learning difficult core concepts in biology. This unit and its learning gains will be useful for teachers and researchers seeking to develop more effective ways to teach complex information in biology courses. Further work with this unit will be developed to explore modes of student thinking throughout the unit and to investigate components of this unit that most effectively improve learning. DBL has the potential to be a successful approach to reform in biology education, especially for the improved understanding of complex topics like gene expression.

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