

ScholarWorks@GSU

Mission to Planet Markle: Problem-Based Learning for Teaching Elementary Students Difficult Content and Practices

Authors	Peffer, Melanie;Renken, Maggie;Enderle, Patrick;Cohen, Jonathan
Citation	Peffer, M., Renken, M., Enderle, P., & Cohen, J. D. (accepted). Mission to Planet Markle: Problem-based learning for teaching elementary students difficult content and skill. Research in Science Education. https://link.springer.com/article/10.1007/s11165-019-09875-z .
DOI	https://link.springer.com/article/10.1007/s11165-019-09875-z
Download date	2026-04-11 23:14:30
Link to Item	https://hdl.handle.net/20.500.14694/10126

1 Running Head: PROBLEM-BASED LEARNING OUTCOMES

2

3

4

5

6

7

8

9

10

11

12

13

14 Mission to Planet Markle: Problem-Based Learning for Teaching Elementary Students Difficult

15

Content and Practices

16

17

18

19

20

21

22

23

24

25

26

27

28

29

30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54

Abstract

Young children can struggle to learn difficult disciplinary content and important skills for practicing science. Problem-based learning (PBL) may be useful for addressing such difficulties, yet evidence to support its usefulness in elementary school-aged children is limited. We considered the role of a PBL unit in improving students' genetics content understanding and their skills specific to creating arguments with coordinated claims, evidence, and reasoning. First-through fifth-grade students participated in a six-week PBL unit about evolution and genetics. Students worked in mixed age groups and were charged with illustrating a fictitious alien species, called markles, based on a series of facts they collected about factors expected to impact markle adaptation. This work was particularly unique in its assessment of student groups' illustrated design solutions as arguments. Although students demonstrated weaknesses in coordinating claims and evidence overall, they were able to demonstrate success in gaining difficult genetics content knowledge and in preparing arguments with, at minimum, two components of well-constructed arguments, in most cases, providing a claim supported by reasoning. This work is informative for understanding student abilities, the potential of PBL, and considerations for its use.

Keywords: Problem-based learning, genetics education, argumentation, elementary science education

55 Mission to Planet Markle: Problem-Based Learning for Teaching Elementary Students**56 Difficult Content and Practices**

57 Problem-based learning (PBL) is a learner-centered approach to instruction. In a PBL
58 context, the learner develops a solution to a defined problem through research and the
59 application of his or her knowledge and skills (Savery, 2015). PBL has been touted for its
60 effectiveness in garnering a host of education-relevant outcomes across disciplines. By engaging
61 students in practical, experiential learning, a PBL approach in science disciplines is expected to
62 foster students' general science practices and discipline-specific content knowledge in tandem
63 (Dochy, Segers, Van den Bossche, & Gijbels, 2003). Such an approach is in line with *A*
64 *Framework for K-12 Science Education* and the derivative Next Generation Science Standards
65 (NGSS), which emphasize the value in coordinating students' development of science practices
66 and core content knowledge acquisition (NGSS Lead States, 2013; National Research Council,
67 2012).

68 In a thorough review of what and how students learn via PBL, Hmelo-Silver (2004)
69 provides evidence of PBL's effectiveness in advancing students' knowledge base, problem
70 solving skills, and self-directed learning skills following problem-based learning experiences.
71 Unfortunately, a shortage of empirical evidence of what students learn in PBL settings remains
72 despite Hmelo-Silver's acknowledgment of as much over ten years ago. The dearth of evidence
73 is particularly noticeable in K-12 settings (cf. Wirkala & Kuhn, 2011). The domains of learning
74 best supported by PBL in Hmelo-Silver's seminal 2004 review neatly align with three broad
75 domains of learning we consider to serve as *holistic science learning* in the current study:
76 content knowledge, science practices, and 21st century skills. Namely, we examined PBL
77 outcomes related to content knowledge in a genetics domain and the scientific practice of

78 argumentation (Kereluik, Mishra, Fahnoe, & Terry, 2013; Voogt & Roblin, 2012). Prior research
79 has suggested these outcomes may be fostered with PBL. We build on this prior work
80 predominately examining the utility of PBL for older students by considering outcomes of PBL
81 associated with elementary school-aged children. The current study aims to contribute empirical
82 support for incorporating PBL in elementary science curriculum.

83 *PBL for teaching difficult genetics content knowledge*

84
85 PBL use in the classroom, and especially in the K-12 science classroom, abounds (Walker,
86 Leary, Hmelo-Silver, & Ertmer, 2015). Presenting students with ill-structured problems with no
87 single path of inquiry provides students the opportunity to collaboratively assess data provided,
88 refine their ideas, and experience the tenuous nature of science knowledge by deciding on a
89 solution that may not be correct (Gallagher, Stepien, Sher, & Workman, 1995). The popularity of
90 PBL as a pedagogical approach may be due to its expected ability to engage students in learning
91 difficult content. One such challenging content area for school-aged students is genetics. For
92 instance, an analysis of genetics themed essays written by high school students indicated the
93 prevalence of many misconceptions (Shaw, Van Horne, Zhang, & Boughman, 2008). This is
94 particularly concerning since before the Next Generation Science Standards, genetics education
95 began in middle school (National Research Council, 1996) and now begins in elementary school
96 (NGSS Lead States, 2013). In spite of years of instruction in genetics, these misconceptions
97 persist. Children are introduced to terms such as “genes” and “genetic inheritance” passively
98 from the entertainment industry but are unsure what those terms mean (Venville, Gribble, &
99 Donovan, 2005), and such exposure may foster misconceptions that persist through high school,
100 stunting potential genetic understanding gains (Smith & Williams, 2007). Work by Duncan and
101 Reiser (2007) suggests that part of the difficulty with learning genetics is due to challenges

102 associated with reconciling information across different levels, such as how what is occurring at
103 the DNA level impacts what is occurring at the protein level in a cell. Even at the undergraduate
104 level, students do not understand how features are inherited, for example believing that diseases
105 are inherited from biological parents, rather than from genetic material (Henderson & Maguire,
106 2000).

107 Genetics may be learned best in the context of inquiry (Duncan, Rogat, & Yarden, 2009).
108 Previous work demonstrated that genetics-themed PBL units were more effective than direct
109 instruction for increasing eighth-grade students' understanding of genetics content (Araz &
110 Sungur, 2007). Although evidence suggests such instruction is effective for improving students'
111 understanding of genetics, the majority of interventions are designed for high school students,
112 with significantly fewer for middle school and late elementary school (Duncan et al., 2009).
113 Previous work suggests that later elementary-aged students are familiar with the concepts of
114 genetic inheritance (Springer & Keil, 1989), and a learning progression proposed by Elmesky
115 (2013) suggested that curricula should leverage the cognitive abilities of K-5 students to develop
116 a more advanced theory of kinship and genetic inheritability to lay the foundation for
117 understanding gene expression in later grade levels. Similarly, a learning progression by Duncan
118 et al. (2009) proposed fifth- and sixth-grade students should have a basic understanding of
119 inheritance, traits, and DNA. In the 2007 National Research Council Report, *Taking Science to*
120 *School: Learning and Teaching Science in Grades K-8*, the authors conclude that all children,
121 even very young children, are capable of engaging in complex reasoning about the world. This is
122 reflected in the NGSS as genetics content appears in the third-grade standards (NGSS Lead
123 States, 2013). Consequently, interventions and research geared toward genetics learning for
124 students in elementary school, particularly in early grades, are necessary.

125 *Young students' arguments: Coordination of claims, evidence, and reasoning*

126 Beyond promoting acquisition of difficult content knowledge, PBL has been traditionally
127 employed to foster important science practices (Allen, Duch, & Groh, 1996; Baser, Ozden, &
128 Karaarslan, 2017; Bell, 2010; Ferreira & Trudel, 2012; Kolodner et al., 2003; Kwon et al., 2018).
129 For example, in the context of clinical education, medical students who engaged in PBL
130 exhibited enhanced clinical problem solving ability (Savery, 2015). PBL activities can often
131 conclude with students making a final argument in response to the initial ill structured problem
132 (Belland, Glazewski, Richardson, 2011). Argumentation is widely recognized as a critically
133 important practice in science education (Berland & Reiser, 2009; McNeill & Krajcik, 2006;
134 National Research Council, 2012; Ryu & Sandoval, 2012). The ability to engage in arguing from
135 evidence is one of eight core science and engineering practices described in the NGSS (NGSS
136 Lead States, 2013). According to the NGSS, students in elementary school should be able to
137 identify arguments and what makes an argument “good,” particularly with regard to evidence.
138 The standards also state that both early and late elementary school students are expected to be
139 able to use evidence to construct an argument. Teaching students about and through
140 argumentation alongside science content accomplishes multiple curricular goals. When engaged
141 in argumentation and the creation of arguments, students apply content knowledge, engage
142 productively in written and verbal discourse, and begin to understand that science is not a
143 discrete collection of facts, but rather a body of knowledge generated through various discursive
144 and cognitive activities (Manz, 2015). Argumentation encourages science learning as a vehicle
145 for making sense of the world, as opposed to a passive student experience (Berland, Schwarz,
146 Krist, Kenyon, Lo, & Reiser, 2015). Research has shown, though, that argumentation and the
147 creation of arguments is challenging for elementary school students (McNeill, 2011; Ryu &

148 Sandoval, 2012) and middle school students (Belland, Glazewski, Richardson, 2011). In
149 particular, teaching students to support claims with evidence—a key component of scientific
150 arguments—has proven to be a challenge for science educators (Berland & Reiser, 2009).
151 Limitations associated with students’ writing and discourse abilities contribute to challenges in
152 helping students learn to support claims with evidence and in assessing students’ ability to do so
153 (Felton, 2004; Sampson, Enderle, Grooms, & Witte, 2013).

154 Despite its status as an important and widely accepted part of science education, creating
155 high quality arguments remains difficult for students to learn. Prior research has examined the
156 nature of some of students’ difficulties and the impact of curriculum on them (e.g., McNeill,
157 2009; Osborne, Erduran, & Simon, 2004). McNeill (2011) analyzed fifth-grade students’ written
158 arguments over the course of a school year. Student writing was analyzed to determine if it was
159 argumentative in nature and if it contained arguments in a claim, evidence, reasoning format.
160 Overall, students’ argument construction improved over the course of the school year, but when
161 given challenging content, students struggled to make accurate and appropriate arguments.
162 Interviews with participating students revealed that while their overall ability to write scientific
163 arguments had improved, the students still lacked an understanding of the importance of using
164 evidence to support claims (McNeill, 2011). Prior work has demonstrated that, at least by middle
165 school, curriculum that highlights argument components (i.e., claim, evidence, and reasoning)
166 aids students in their ability to ground arguments in evidence (Berland & Reiser, 2009; McNeill
167 & Krajcik, 2006). Berland and Reiser’s (2009) analysis of middle school students’ written
168 arguments revealed two main categories: arguments that explicitly reference evidence and
169 arguments that implicitly reference evidence. The overall ability of students to make high quality

170 arguments explicitly incorporating evidence requires more attention and guidance (Berland &
171 Reiser, 2009).

172 Similarly, Ryu and Sandoval (2012) examined third- and fourth-grade students' argument
173 construction over a period of a school year. Students were engaged in a science curriculum in
174 which their teacher prompted students working in groups to justify how they know something or
175 how they would convince others of what they know. Ryu and Sandoval (2012) assessed
176 arguments based on students' use of causal claims, the coherence of claims, citation of evidence,
177 and whether or not the student explicitly justified their argument. The authors noted
178 improvement over the school year in the students' ability to relate claims to each other in a
179 coherent manner, their ability to cite evidence, and the use of explicit justification. These
180 developments were attributed to explicit and consistent guidance offered to students through
181 expectations for arguments that were communally established among teachers and students.
182 Although improved, students' ability to explicitly justify their claims with data was still lower
183 than the other aspects of argumentation examined in the study (Ryu & Sandoval, 2012). These
184 studies, as well as others in the argumentation literature (Sampson & Clark, 2008), demonstrate
185 students' challenges with respect to explicitly supporting claims with evidence in written
186 arguments, especially in classroom settings. Further, challenges persist in the use of curricular
187 interventions to help students with connecting claim and evidence (McNeill & Berland, 2017).

188 PBL activities are one type of curricular intervention that can foster productive
189 argumentation interactions (Belland, 2010). PBL frames instruction with a context, or issue,
190 requiring students to know and use relevant scientific information (Hmelo-Silver, 2004).
191 Students can use scientific information to lead an investigation or to design a solution. For
192 example, to create a PBL context that fosters productive argumentation, some PBL units revolve

193 around a broad, investigable question that can lead to multiple productive investigations. Other
194 PBL units employ a problematic, ill-structured context, usually drawn from real world
195 circumstances, that necessitates the design of potential solutions (Householder & Hailey, 2012).
196 Real world problems are typically messy, lacking the type of well-defined nature that often
197 mitigates students' motivation or engagement. The real-world context requires students to set
198 parameters and pull resources from a variety of disciplines (Savery, 2015). When framing a PBL
199 unit in the real-world context, students' endeavors change in nature from one focused on
200 conducting scientific investigations to the designing and refining of problem solutions. Although
201 both are emphasized in national standards (NGSS Lead States, 2013), the integration of design
202 challenges for the goal of enhancing science instruction remains problematic (Berland, 2013).

203 The argument products developed during design challenges must reflect the unique
204 purpose and kinds of reasoning used for designing a problem solution (Berland, 2013).
205 Theoretical frameworks of argumentation identify several commonly accepted or related
206 structural elements inherent in high quality arguments (Grooms, Enderle, & Sampson, 2015;
207 McNeill & Krajcik, 2006; Osborne et al., 2004; Sampson & Clark, 2008). These frameworks
208 have mostly focused on the production of arguments from scientific investigations and not those
209 arguments that result from design challenges. The nature and characteristics of traditional
210 argument elements (e.g., claim, evidence, and reasoning) must shift to reflect the different
211 activity goal of achieving a problem solution that meets certain criteria and specifications.

212 The first argument element to consider is the *claim*, which is typically an assertion that
213 directly answers the question guiding a scientific investigation (McNeill, 2011). In design
214 challenges, the claim would comprise either a proposed concept from the initial stages that is
215 ideal for developing a prototype. Rather than the assertive statement typical for scientific

216 arguments, the claim in a design argument can encompass a hypothetical schematic or a physical
217 model. When considering *evidence* in a design argument, a design activity shifts the type of
218 information analyzed to support the claim, focusing mainly on the constraints and criteria set
219 forth in the design problem (McNeill & Krajcik, 2006). Finally, the *reasoning* element in a
220 design argument would involve statements that explain how the evidence used for a particular
221 stage supports the claim being made in that stage (Sampson & Clark, 2008). For design
222 arguments, these statements would emphasize how elements of the prototype design (claim)
223 align with the constraints and criteria stemming from the design problem (evidence). In the
224 current study, we examined students' illustrated products at the end of a problem-based learning
225 unit for indication of three component parts of an argument: claim, evidence, and reasoning. One
226 of our research objectives was to determine if elementary students were able to support
227 illustrated claims with evidence.

228 *Illustrated design solutions as arguments.* When focusing on the ability to construct high
229 quality arguments, many studies have analyzed written text created through students' activities
230 (Berland & Reiser, 2009; McNeill, 2011; Sampson et al., 2013). By assessing text-based
231 products, such research has shed light on students' understanding of specific science content and
232 the structural elements that make up scientific arguments. Further, written arguments serve as
233 proxies, representing students' proficiency with engaging in the process of arguing from
234 evidence (Sampson et al., 2013). However, written text is not the only manner available for
235 students to express an argument composed of claims, evidence, and reasoning.

236 Drawings and graphic representations, compared to text-based forms, are considered to
237 be equally valid products for assessing students' understanding of complex systems and
238 phenomena (Bowker, 2007; Dentzau, in press; Lewis & Greene, 1983; White & Gunstone,

239 1992). Scholars have argued that using drawings can make students' conceptions more
240 accessible due to the perception of drawing as being a less intimidating, and often enjoyable,
241 activity compared to writing, particularly for younger students (Chang, 2012; Thomas & Silk,
242 1990). Chang (2012) contends that drawings are also applicable for assessment purposes with
243 small groups of children as well as with individuals. Thus, allowing young students to generate
244 drawings to represent conceptual understanding can also provide a way to decrease apprehension
245 related to learning relatively complex science content, such as genetics. Also, having students
246 draw the representations of different argument components could provide another vehicle for
247 conveying the importance of individual components and relationships between them.

248 **Current Study**

249 The driving question of the current study was whether PBL supports gaining content
250 knowledge and science practices. The PBL unit utilized for this study introduced students to the
251 concepts of genetics and evolution and concluded with a capstone argument design project.
252 Given that we know very little about PBL to teach genetics and develop arguments at the
253 elementary school level, we sought to preliminarily examine each individually. We assessed
254 student genetics understanding at the beginning and end of the unit using a pre/posttest format.
255 To assess students' ability to create arguments, we asked student groups to create a capstone
256 argument design project to complete a PBL unit that removed writing demands, the potential
257 impact of prior belief bias, and the possibility of a correct answer. Students were instructed to
258 generate a creative, illustrated product rather than a written argument. We hypothesized that
259 asking students to generate drawings rather than written arguments would make generating
260 arguments supported by evidence more accessible to elementary school students. In other words,
261 we expected to observe evidence-based claims in student groups' collaborative illustrations.

262 **Methods**

263
264 *Participants*

265 The participants in this study were 80 elementary students in grades 1 through 5 at a Title
 266 I elementary school located in a suburb of a large southeastern city (Table 1). Title I schools
 267 contain a significant proportion of children from low socioeconomic status families and receive
 268 federal funding to help children meet state and academic standards. 57% of the students at the
 269 participating elementary school were below the poverty line. At the time of this study, schools
 270 implemented grade-appropriate Georgia Performance Standards (GPS) as the measure of
 271 benchmarks for all academic subjects, but in 2016 the Georgia State Board of Education
 272 approved a new set of standards titled the Georgia Standards of Excellence (GSE) for schools to
 273 adopt during the 2017-2018 school year (Georgia Department of Education, 2015).

274 Table 1. Grade distribution of Participating Students

	<i>n</i>	<i>% of Total</i>
<i>First Grade</i>	10	12.5%
<i>Second Grade</i>	16	20%
<i>Third Grade</i>	21	26.3%
<i>Fourth Grade</i>	11	13.8%
<i>Fifth Grade</i>	22	28%

275
 276 All 80 students participated in the PBL unit and design argument assessment. Data used
 277 for the genetics knowledge assessment involved only the 67 students who were present in school
 278 during both the pre and posttest. These 67 students were comprised of 9 first graders (13%), 10
 279 second graders (15%), 17 third graders (25%), 11 fourth graders (16%) and 20 fifth graders

280 (30%). Students participating in this study were a mix of talented-and-gifted (TAG) and able
281 learners (i.e., students above grade level on a measure of math or reading ability, or both).
282 During the daily enrichment period, (see intervention procedure below), TAG and able learners
283 engaged in PBL with the school gifted coordinator and support staff including the media
284 specialist, art teacher, math coach, and counselor. Participants were 52.6% female and 46.2%
285 male. One student declined to identify gender. We did not collect race/ethnicity data, but the
286 school district of the participating school is 48% African-American, 37% Caucasian, 8%
287 Hispanic, 4% Multi-racial and 3% Asian.

288 *Unit design and intervention procedure*

289 The intervention took place over six weeks during the daily enrichment period at the
290 research site school. The enrichment period took place from Tuesday to Thursday for 45 minutes
291 a day in the school media center. During this window of time, students school-wide were moved
292 to classrooms or school sites that were not their homerooms for remedial or enrichment time.
293 Students who participated in the study were assigned to enrichment rather than remediation
294 support. This was the third PBL unit students in this group had participated in during the school
295 year, but it was the first unit focused on biology learning. Enrichment period PBLs were
296 designed to align with specific standards that would be addressed in the students' homeroom
297 class for a deeper level of engagement. During all PBL units, students worked collaboratively
298 around a central theme or question. The first PBL unit that students engaged in was a school
299 courtyard redesign project. Students worked in groups to design the space and create a budget for
300 the redesign. Their final projects were presented to a board of community stakeholders and
301 school staff. The second PBL unit was focused on students using scientific reasoning skills to
302 solve a mystery, namely why a farmer's chickens stopped laying eggs. Students were divided
303 into 16 mixed-age groups, with 6-7 students in each group. Students from each grade level were

304 represented within each group, but distribution varied. Each day, the student groups worked
305 through a PBL activity related to genetics and evolution, specifically on animal adaptations.
306 Under the Georgia Performance Standards, approved in 2004, animal adaptations in relation to
307 the environment are introduced as a framework in the first grade; each grade builds on that
308 foundational understanding, but genetics is not included as a distinct unit until the fifth grade.
309 Additionally, these standards identify science communication through writing and drawing as a
310 key competency starting in the first grade and introduce scientific argumentation in the third
311 grade (Georgia Department of Education, 2015). Under the new Georgia Standards of
312 Excellence, the content areas are identical to the previous standards, but the focus has shifted to
313 more inquiry-based instruction.

314 To start the PBL unit, students were introduced to a fictional scenario in which a group of
315 scientists were dispatched to study organisms called markles, who live on a planet far out of the
316 solar system, Planet Markle. However, the scientists in the scenario are concerned that the
317 markles may evolve and consequently change their appearance during the extended time period
318 of travel from Earth to Planet Markle. Therefore, students were placed in the role of Mission
319 Planners. As Mission Planners, they hypothesized about the appearance of the markles and
320 devised plans for capturing the creatures, based on information on basic genetics principles
321 presented earlier at a series of stations as part of the PBL unit, information provided about the
322 markles' home planet, and the students' own claims about the markles' appearance, respectively.
323 Although fictional, the problem space mimicked that of a real world context. It lacked a rigid and
324 clearly-defined problem space and required students to use information from a variety of sources.

325 At the beginning of the unit, students were instructed to visit stations to learn how
326 animals on Earth change their appearance over time. Each of the four stations had its own

327 learning objectives, questions to answer, and after completing the station, students earned a
328 factoid (Table 2) related to both their station and fictional markle biology. The first station was
329 titled “Genes, Environment, and Phenotypes: Why do we look the way we do?” and introduced
330 students to the concept of cells containing DNA, the hereditary nature of DNA, and how both
331 DNA and the environment can influence our phenotype, or how we look. Students completed the
332 Dragon Genetics simulation to model how genes influence phenotype, and how this information
333 is passed between parents and offspring. Students also learned about how heat influences the
334 coat color of Siamese cats. The second station, “Adaptations,” introduced students to the concept
335 of adaptations, gave examples of adaptations, (e.g., long necks on giraffes), and described how
336 adaptations can form over time due to evolutionary forces (e.g., Galapagos finches). The third
337 station was titled “Mutations and Survival” and introduced students to mutations (changes in
338 DNA), and how mutation can lead to new adaptations and evolution. Students explored the
339 relationship between mutation and color in pepper moths using an online lesson and
340 accompanying game (peppermoths.weebly.com). The final station, “Genetic Drift and Natural
341 Selection,” explored how different processes influence the number of genes that are available
342 impact a species. Students learned about extinction, non-random selection of genes (natural and
343 artificial selection), and random removal of genes via genetic drift. Students played a game
344 developed by the first author to demonstrate natural selection and genetic drift. For the natural
345 selection demonstration, students took several butterflies and were told that they represented the
346 total population of butterflies in a backyard. Some butterflies contained lots of decoration
347 whereas others were plain. Students then selected half of the butterflies to go into their private
348 collection, and then discussed how removal of those particular butterflies changed the diversity
349 of phenotypes, and consequently genes present in the population. During the second part of the

350 demonstration, students removed 20 numbered beetles from a bag, half green and half orange.
351 Students first counted how many of each type of beetle was present and wrote it in their
352 notebook. Then students rolled a 20-sided die five times. If a beetle's number was selected, it
353 was turned over and considered dead. Students then counted how many orange and green beetles
354 were left after some were randomly removed from the population. This process was repeated at
355 least once more and numbers compared to demonstrate the random impact on the population.
356 Upon completion of each station's activities, students earned a sticker with a factoid relevant to
357 markle adaptations. A list of factoids collected at each station is in Table 2.

358 After students completed all of the stations, they were randomly assigned features of a
359 particular region of Planet Markle. Examples of these features are shown in Table 3. Based on
360 these features, students drew what they thought the markles in their region would look like.
361 Students also were told to design a trap to capture the markle based on their predictions of the
362 creatures' appearance and behavior. Each student group prepared a presentation during which
363 students described their markle and their plan for trapping the markle. To support their
364 presentations, students prepared notecards with details about the markle and trap design.
365 Students received no instruction on argumentation or scientific explanation.

366 Unscripted scaffolds were provided by the five instructors present during instructional
367 focus time and by the series of stations at which students learned genetics principles. The first
368 author assessed fidelity of curriculum implementation by visiting the school site once a week to
369 observe the unit. The first and second authors attended the students' concluding presentations to
370 make observations and to collect student artifacts, including the groups' illustrations and notes.

371

372 Table 2. *The factoids students earned upon completing each station. The students integrated*
 373 *these factoids into their final markle drawings.*

Station	Factoid
Genes, Environment, and Phenotype	Markles inherit different genes from their parents. Since these genes lead to certain phenotypes, if a markle has one parent with spotted fur (and the gene for spotted fur), they will also have spotted fur. When a markle is born, it is light colored. If the markle grows up in a cold climate, it will eventually be blue. Their blue color helps them blend in with the water, so blue markles tend to live near water and eat fish. Markles that grew up when it is warmer are green and live in the trees where they can blend in better with their surroundings. Markles want to blend in with their surroundings so other animals do not eat them.
Adaptations	Markles have different adaptations that they use to find food, escape predators, and have babies. These adaptations include big noses, long legs, long hair to help camouflage and keep the markle warm, wings for flying, snorkels, and suction cup hands. Big noses and snorkels help the markles find food. Without the snorkels, markles can't go fishing for food. Their big noses help the markles sniff out food and without them, they would be limited to only using their eyes to look for food. Giant bears can eat markles. The giant bears are slow and because of their size, can't climb trees to chase after the markles. Therefore, if a markle has adaptations such as wings, long legs or suction cup hands for climbing the markle is more likely to get away. Without these adaptations, the markle relies on camouflaging behind its long hair, or its color. Remember, much like the finches we learned about in this station, although all markles are similar, they have different adaptations depending on their specific environment. As the markles' environment changes over the time it takes for our astronauts to arrive, the markles' adaptations will also change.
Mutations and Survival	Some markles will be albino (all white) because of a random mutation. Being albino can be good or bad depending on whether there is lots of snow on the ground or not since the markle can hide better on a white background. If there is no snow on the ground, the albino markle can't hide easily and is more likely to be eaten by predators.
Genetic Drift and Natural Selection	There are many volcanoes on Planet Markle. These volcanoes can kill markles that get stuck in the lava flows. The volcanoes can also spread ash everywhere turning all of the trees from green to white. Some markles have spots on their fur. Next to Planet Markle is a planet where a species of aliens called narps. Narps love to wear spotted markle fur and hunt spotted markles for their fur.

374

375

376 Table 3. *Sample features of Planet Markle geography that were distributed to students after*
 377 *completing all of the unit stations. Students based their choices regarding the markles'*
 378 *morphology and the features of traps designed to catch the markles on the random combination*
 379 *of Planet Markle features they received.*

Sample Features of Planet Markle Geography

Your region is very cold.

Your region of Planet Markle is very dark and it is difficult to find food using eyesight alone.

Your region of Planet Markle has large cliff faces. Birds like to nest high on these cliff faces, and markles love to eat their eggs.

Your region is susceptible to tidal waves and markles are at risk for drowning without certain adaptations.

Your region is in a desert with lots of quicksand.

380

381

382

383 *Data collection and analysis*

384 We collected data associated with our primary research questions, including students'
385 genetics content knowledge and illustrated design arguments. Content knowledge was collected
386 at the individual level, while illustrated design arguments were completed in groups.

387 **Genetics assessment.** Previous work identified common genetics misconceptions held by
388 students in high school (Shaw et al., 2008). Since these misconceptions persist and may begin in
389 the early elementary grades (Smith & Williams, 2007) we decided to focus our assessment on
390 these common misconceptions, rather than a comprehensive assessment of everything learned
391 during the PBL unit. In order to determine if engagement in PBL resulted in enhanced
392 understanding of these particularly difficult to understand genetics concepts, we asked students
393 to do a pre/posttest assessment of their understanding of two of domains of these common
394 misconceptions: (1) the deterministic nature of genes and (2) the nature of genes and genetic
395 material. We asked students two questions related to the deterministic nature of genes: Why do
396 people look different from each other? Why don't all people have the same hair color? We asked

397 students one question about the nature of genes and genetic material: What are genes? The three
 398 items were open ended. Students answered the items at the beginning and end of the PBL unit.
 399 We removed data from students who were absent during either the pre or posttest. Sixty-seven
 400 students participated in both the pretest and posttest.

401 Student responses were blinded and then coded by two researchers on a scale of 0-4,
 402 where 0 = no response and 4 = mature understanding. A summary of the rubrics used is shown in
 403 Table 4. When coders disagreed, a third researcher served as the tiebreaker. Interrater reliability
 404 for this coding was acceptable for all three questions (Question 1, Cohen’s *kappa* = 0.92;
 405 Question 2, Cohen’s *kappa* = 0.93; Question 3, Cohen’s *kappa* = 0.81).

406

407 *Table 4. Rubric for coding students’ responses to genetics assessment items.*

Score	Questions 1 and 2	Example Answer	Question 3	Example Answer
0	No response, illegible, unintelligible or “I don’t know”		No response, illegible, unintelligible or “I don’t know”	
1	No attempt at explanation, restates the question	People weren’t born the same	Mentions characteristics controlled by genes such as skin or hair color. No mention of parents, inheritance, or DNA.	Genes are a type of animals like cats. All cats are in the same genes
2	Non-biological explanation (God, ethnicity, culture)	Because God made them that way	Describes genes as cells or traits. No mention of heritability.	Genes are things in your body that give you characteristics
3	Biological explanation that includes understanding of family, parents, or	Our parents did not look the same so we are most likely not	Mentions concepts of inheritance, but does not fully explicate what genes are. Describes genes as	Genes are things that are passed on from your parents

	inheritance. Does not mention genes	to look the same as our parents	traits or generic “things” that come from parents.	
4	Explicitly mentions genes, genetics, inheritance	People look different from one another depending on the genes they receive from their parents	Explicitly mentions DNA. Makes connection between DNA and a trait or relationship to parent.	Genes are the DNA in your body that determines who you are and what you look like

408

409

410 **Design argument assessment.** We collected group-generated design drawings and
 411 supporting presentation notecards for data analysis. Notecards contained details about illustrated
 412 markles and traps that students felt were most important to their presentations. Students received
 413 no direct instruction regarding what information to include on their notecards. Brooks (2009)
 414 contended that one of the strengths of using drawings for students to express their understanding
 415 lies in the ongoing facilitation of dialoguing in other modes (such as writing) that help students
 416 explore complex ideas. In light of this connection, we chose to include the presentation notecards
 417 in the argument analysis in an attempt to fully capture student groups’ use of evidence and
 418 reasoning in their design solution. Final products were evaluated by assessing the presence of
 419 claims, evidence, and reasoning elements in the drawings and notecards.

420 Being a design challenge, we analyzed students’ work using adapted conceptualizations
 421 of argument components (claim, evidence, reasoning) (McNeill & Krajcik, 2006) better suited
 422 for design challenges as opposed to scientific investigations. Broadly speaking, these three
 423 elements of written arguments provide different kinds of information to a reader. The claim is an
 424 answer to the problem or question posed in a particular context (Sampson, Enderle, & Grooms,
 425 2013). Although, structurally, the claim is typically provided first, these answers are ultimately

426 derived from the evidence generated during an investigation or development of a problem
427 solution (Sampson et al, 2013a). Evidence in scientific arguments entails the data and
428 information that has been analyzed and interpreted, involving the identifications of trends,
429 patterns, comparisons, and contrasts. The reasoning component of an argument involves making
430 connections between the claim and evidence using design principles and scientific concepts
431 (Sampson et al, 2013a).

432 With respect to *claim* in the Markle design challenge, the groups' markle drawing was
433 considered to be the overarching claim as it represented the actual solution to the design
434 challenge embedded in the PBL unit. Specific features of the markle highlighted in the drawings
435 or notecards were also considered as claims. We characterized *evidence* as the environmental
436 constraints, in the form of factoids or Planet Markle features, provided to the student groups
437 during the unit. For evidence to be considered present in the groups' design arguments, either
438 explicit drawings of the environmental elements described in the factoids or features, or explicit
439 statements describing them in the notecards had to be included. Although we do see instances
440 where students choose features directly from the factoids, this is not always the case. It is likely
441 that reasoning occurred at different levels, with some creative ventures pursued while the
442 factoids are utilized generally. Finally, *reasoning* elements included drawings or statements that
443 connected particular features of the markle to the environmental constraints identified by each
444 group. Typically, reasoning statements involved descriptions of the function or purpose of a
445 certain feature in relation to a specific environmental constraint.

446 The drawings and notecards for sixteen student groups were analyzed using the design
447 argument framework described. The first and third author collaborated on this analysis, reaching
448 agreement on coding through continuous negotiation until agreement was reached. The third

449 author was not part of the team who administered the PBL unit to students, so was not biased as
450 to how students generated drawn arguments. The analysis focused only on the design solutions
451 generated for the markle organism, as these solutions required the consideration of
452 environmental constraint information collected through student activity and markle traps did not.
453 Thus, the trap designs are not discussed further here. The use of environmental constraint
454 information as evidence required students to build on their understanding of the genetic and
455 environmental concepts taught during the station activities at the beginning of the PBL unit. The
456 analysis quantitatively analyzed the presence and frequency of various combinations of claim,
457 evidence, and reasoning components present in each groups' set of drawings and notecards. The
458 analysis of groups' drawings included counting drawn and written components present and their
459 nature, while the notecards were analyzed for the presence of various combinations of written
460 argument components. Our focus for this analysis was to describe the variation of argument
461 structures produced by students who engaged in the Markle PBL unit. We did not engage in an
462 evaluation of the quality of these elements, as our research focus pertained more to
463 understanding what kinds of elements emerged in students' arguments when afforded
464 opportunities to draw them instead of just writing text for them. Following this analysis, we
465 identified several groups to further describe using small case studies (Stake, 2006) to
466 demonstrate and compare some of the variations in the design solutions generated.

467 **Results**

468 *Students' understanding of genetics after engaging in PBL*

470 Since little is known about genetics learning in elementary school students and very few
471 interventions have been developed to improve genetics understanding in elementary school
472 students (Duncan et al., 2009), we first determined if students engaged in a genetics PBL

473 demonstrated learning gains, particularly gains in traditionally difficult to understand genetics
474 concepts. To assess changes in genetics understanding, specifically the relationship of genotype
475 to phenotype and the nature of genes, students ($n = 67$) completed pre and posttest items.
476 Performance on the both the pretest and posttest was normally distributed. First, we conducted a
477 paired sample t -test to compare the pretest and posttest means. Responses on the posttest ($mean$
478 $= 3.05$, $SD = .45$) were significantly different than responses on the pretest ($mean = 2.68$, $SD =$
479 $.66$; $t = -2.32$, $df = 19$, $p = .03$, *Cohen's d* $= .66$). Next, we examined if student performance on
480 all three of the genetics test items improved between the pre and posttest. For the first two items,
481 Why do people look different from each other?; Why don't all people have the same hair color?
482 within-subjects paired t -tests revealed a statistically significant increase in conceptual
483 understanding from pretest to posttest (Question 1: pretest $M = 2.89$, $SD = 1.14$; posttest $M =$
484 3.25 , $SD = 1.13$; $t(66) = -2.20$, $p = .03$, *Cohen's d* $= 0.32$; Question 2: pretest $M = 2.97$, $SD =$
485 1.18 ; posttest $M = 3.35$, $SD = 1.06$; $t(66) = -2.14$, $p = .04$, *Cohen's d* $= 0.34$; Figure 1). Using a
486 third within-subjects paired t -test, we did not observe a statistically significant difference in
487 students' understanding of the nature of genes between the pretest and posttest (Question 3:
488 pretest $M = 2.22$, $SD = 1.13$; posttest $M = 2.17$, $SD = 1.26$; $t(66) = 0.26$, $p = .80$, *Cohen's d* $=$
489 0.04 ; Figure 1)¹.

490

Place Figure 1 Here

¹ We noted that second graders performed more poorly on the posttest for Question 3 than did other grade levels (Figure 2). However, when we omitted second graders' data from the analysis, there were still no statistically significant gains between pretest and posttest for Question 3. Figure 1 illustrates pretest and posttest scores for Question 3 with second graders included.

514 differently at pretest on Questions 2 or 3. However we did observe a statistically significant
515 difference on pretest performance for Question 1 ($F(4,62) = 4.70, p = 0.00$). Post-hoc analysis
516 with Fisher's least significant difference test indicated that fifth graders' pre-test scores ($M =$
517 $3.17, SD = 1.23$) were statistically higher than all of the other students' scores (first grade, ($M =$
518 $2.30, SD = 1.23$); second grade ($M = 2.50, SD = 1.22$); third grade ($M = 2.57, SD = 1.17$); fourth
519 grade, ($M = 2.54, SD = 0.97$).

520 *Characteristics of student-generated design solution arguments*

521 Reviewing the products generated by student groups during the markle design activity
522 revealed interesting trends. Overall, the different groups were able to incorporate the
523 environmental constraint information in their designs of a markle. Across all groups, features
524 were included in each markle design that could be reasonably connected to the specific
525 environmental factoids each group received during the first part of the unit. Thus, at least
526 anecdotally, evidence exists that all student groups were able to process the environmental
527 constraint factoids and develop designs responsive to them. However, the analysis described here
528 does not include any inferred or anecdotal connections between students' designs and relevant
529 environmental constraints. The following analysis first focuses on general trends in explicit
530 elements, either drawn or written, included in the markle design presented to the other groups.
531 As these designs represent complete argument products emerging from the unit activities, they
532 were the primary unit of analysis. We expanded that unit to also include the notecards that were
533 prepared for the presentation in an effort to capture as many connections as possible being made
534 by students between design features (claims), environmental constraints (evidence), and the
535 relevant functions of those features (reasoning).

536 The analysis of all groups' arguments involved both the actual drawing presented and the
537 presentation notecards prepared by the students. Table 5 provides an overview of how student
538 groups incorporated different argument elements in the drawing they presented. Recall, two
539 primary aims of this study were to investigate whether elementary students are able to coordinate
540 claims, evidence, and reasoning and how the creation of illustrated arguments relate to this
541 ability. All groups developed a drawn design, so at minimum, they all produced a drawn claim.
542 However, a claim alone is not an argument. Six out of 16 groups (38% of the groups) only
543 provided a drawn design/claim with no other supporting information, thus not providing an
544 argument in their final design solution. Three more groups only included written labels with their
545 drawings to highlight certain features. This means the majority, approximately 56%, of the
546 groups did not provide an argument in their illustrated design solutions. The remaining groups
547 did incorporate explicitly some combination of argument elements in their presented design
548 solution. Only one group explicitly incorporated constraint information through drawing, using
549 illustrated evidence about the environment to support markle features they developed. This group
550 also included written reasoning statements to describe the functions of their design relative to the
551 environment. Another group only included written reasoning statements with their drawing that
552 described the functions of specific design features. Finally, five student groups included several
553 written statements on their presented designs that incorporated combinations of the different
554 argument elements, with some statements including both evidence and reasoning and some with
555 only reasoning included. It is worth noting that all of the illustrated arguments included text on
556 the illustration, with the exception of a single drawn claim plus drawn evidence argument.
557 However, even in this case, the group included a written reasoning statement on their illustration.
558 We describe this group in more detail as a case study later.

559 *Table 5. Quantitative Comparison of Claim-Evidence-Reasoning (CER) Elements in Drawings*
 560

	CER Elements in Drawings	# of Groups	% of Groups
	Drawn C Only	6	38%
No illustrated argument present	Drawn C with Written Label Only	3	19%
	Drawn C with Drawn E & Written R	1	6%
Illustrated argument present	Drawn C with Written C, E & R elements	5	31%
	Drawn C with Written R Only	1	6%

561 Note: C = claim, E = evidence, R = reasoning.

562 The analysis of the notecards provided a more complex view of how each group
 563 incorporated different elements of evidence and reasoning in the final design solution they
 564 presented. Table 6 provides a quantitative description of the different combinations of argument
 565 components present on the notecards for each group. Each statement on a group’s notecard was
 566 analyzed individually for argument components. In some instances, pairs of sentences were
 567 analyzed together as they comprised one coherent unit of argument elements. Although more
 568 complex in the distribution of combinations, broad trends are readily apparent in the table. First,
 569 the majority of the statements students wrote on their notecards emphasized connections between
 570 certain features of their markle design (claim) and their function (reasoning). Yet, it is notable
 571 that student groups were more explicit in being sure to call out specific environmental constraint
 572 evidence to support the features of their markle design for their presentation, either separately or

573 in combination with elements of reasoning, rather than paired with their claim. Thus, in the
 574 overall analysis of the groups' final design solutions, student groups' ability to incorporate
 575 argument components was more prevalent in their written notations as opposed to in their
 576 illustrated forms. Nevertheless, it is important to note that the illustration provided a point from
 577 which claims, evidence, and reasoning could emerge.

578 *Table 6. Quantitative Comparison of CER Elements in Notecard Statements*
 579

Group	C Only	E Only	C + E	C + R	C+E+R
A				6	
B				1	2
C	1			4	2
D				2	3
E				8	
F	1	1		5	1
G			2	1	1
H	4			1	2
I		2	3	1	1
J	1	2	1	5	
K				7	2
L					
M					
N					
O	2			2	2
P			1	6	1

580

581 *Variations among student groups: Four cases*

582

583

584

585

586

To provide further insight into the kinds of design solutions developed by elementary students in this activity, we provide a more detailed description of four student groups, with each group serving as a case for this part of the analysis. The four cases were selected to represent unique solutions to help the reader see the nature of the design solutions presented. Table 7 provides pictures of each group's markle design and other relevant information.

587

588

589

590

591

592

593

594

595

596

597

Group E: A case of drawn evidence. Only one group out of 16 explicitly drew design constraints, or evidence as conceptualized here. The environment constraints related to the presence of lakes and “tall trees” in the markle’s environment are prominent elements in Group E’s drawing. The few written statements included in the group’s drawing focus only on reasoning elements, describing the function of certain features (e.g., “Claws for digging and killing prey”, “Wings for flying and propelling through water”). Interestingly, though they were the only group to draw evidence, they were also one of the only groups that did not include evidence in their written notecard. Example statements from their notecards include a string of several claim and reasoning combinations: “The wings are to fly and propel through water. The eyes for night vision. Fangs for biting prey. Gills for swimming. Claws for killing prey and digging wandering around. Changing color of fur.”



598

599

600

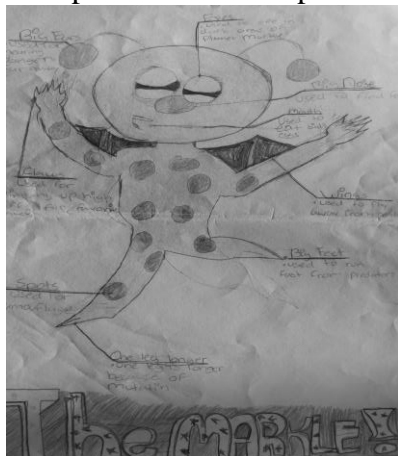
This group provided one of the largest amounts of written argument combinations on its notecard as well. The group composition was relatively equal in its distribution across grade levels, with two first graders, and one student from every other grade level, second through fifth.

Table 7. Comparison of Student Group Cases

Drawing	Environmental Constraints/Evidence	CER Elements - Drawing	CER Elements - Notecards	Students' Grade Level
<p>Group E– Drawn Evidence</p> 	<ul style="list-style-type: none"> • Your region has large cliff faces. Birds like the nest high on these cliff faces, and markles love to eat their eggs. • All of the lakes in your region of Planet Markle contain large markle-eating sea monsters. • Giant snakes that like to eat markles live in your region. These giant snakes can't see markles that are hidden well. • Your region is susceptible to tidal waves and markles are at risk for drowning without certain adaptations. • Your region is full of tall trees 	<p>1 Drawn C 2 Drawn E 3 Written C+R</p>	<p>8 C+R Statements</p>	<p>1st – 2 2nd – 1 3rd – 1 4th – 1 5th – 1</p>
<p>Group A – Younger Group with Large Amount of Reasoning on Drawing</p> 	<ul style="list-style-type: none"> • Your region is very cold • Your region is very snowy • Your region is full of tall trees • Your region of Planet Markle has large cliff faces. Birds like to nest high on these cliff faces, and markles love to eat their eggs • Your region of Planet Markle is very dark and it is difficult to find food using eyesight alone 	<p>1 Drawn C 6 Written C+R</p>	<p>6 C+R Statements</p>	<p>1st – 2 2nd – 2 3rd – 2 4th – 0 5th – 1</p>

Drawing

Group K – Older Group with Large Amount of Reasoning on Drawing



Constraints

- Your region is very dark and it is difficult to find food using eyesight alone
- Your region has large cliff faces. Birds like the nest high on these cliff faces, and markles love to eat their eggs.
- Your region has very few trees and rives full of fish
- Your region is in a desert with lots of quicksand
- Your region produces gamma rays that cause mutations in your markles that change their fur color

CER-Drawing

- 1 Drawn C
- 3 Written C+E+R
- 6 Written C+R

CER-Notecard

- 2 C+E+R Statements
- 7 C+R Statements

Grd. Lvl.

- 1st – 1
- 2nd – 1
- 3rd – 2
- 4th – 2
- 5th – 1

Group G – Only Claim Drawn, Notable Written Evidence



- Your region has large cliff faces. Birds like the nest high on these cliff faces, and markles love to eat their eggs.
- Your region if full of tall trees
- Your region is susceptible to tidal waves and markles are at risk for drowning without certain adaptations
- Your region contains lots of large beaver-like animals that cut down all of the trees to build dams
- Aliens from Planet Narp want the markles spotted fur.

CER-Drawing

- 1 Drawn Claim

CER-Notecard

- 2 C+E Statement
- 1 C+R Statements
- 1 C+E+R Statement

- 1st – 1
- 2nd – 2
- 3rd – 1
- 4th – 1
- 5th – 2

1 **Groups A & K: The impact of age.** Two other groups who both incorporated a larger
2 number of reasoning statements in their drawing and notecards also provide a contrast in group
3 structure. Group A was markedly younger, with most members being in third grade or below.
4 They provided reasoning elements explaining the functions of each design feature they
5 highlighted in their drawing for a total of six, such as “Long legs to climb,” (Written C+R) and
6 “Three eyes for good eyesight.” (Written C+R) Most of these statements were repeated in their
7 presentation notecards.

8 Similarly, another group, Group K, provided a slightly larger amount of statements with
9 argument components on both their drawing and notecards. The age composition of this group
10 skewed slightly older as the majority of student members were in third grade or older. A notable
11 difference in the statements provided by this group involves their use of explicit references to
12 environmental constraints as evidence to support certain design features. On their drawing, the
13 group wrote statements including, “Claws used for climbing up high cliffs for favorite snack.”
14 (Written C+E+R) Similar statements were included on the group’s notecards, such as, “Eyes:
15 These eyes are used to see in the dark areas of Planet Markle.” (Written C+E+R) Although this
16 group did incorporate evidence in some of their statements, the majority of their written
17 statements involved only claim and reasoning elements. Thus, both groups, although comprised
18 of different age concentrations, demonstrate the ability to incorporate relevant argument
19 components in explaining their design solutions. The presence of more explicit references to
20 constraint information as evidence from the older group of students does suggest a
21 developmental emergence of understanding the need to coordinate multiple argument
22 components.

45 Although genetics is typically taught to older students (Duncan et al., 2009), we observed
46 that the elementary-aged students participating in this PBL unit increased their understanding of
47 genetics principles that are typically misunderstood. Third graders experienced significant gains
48 in their overall genetics understanding after participation in the PBL. More specifically, we noted
49 that students' understanding of the deterministic nature of genes were most likely to improve.
50 Students' understanding of the nature of genes and genetic material did not improve, which may
51 indicate that this is a particularly difficult concept for young students to grasp and likely requires
52 additional instruction beyond what was provided at the unit stations. Regardless of grade level,
53 following the PBL unit, students were more likely to explicitly reference genes, inheritance, or
54 genetic material when asked why people look different from one another. When asked about hair
55 color, however, there was a variation in improvements in conceptual knowledge across grades.
56 Specifically, first graders showed a slight decrease in performance from pretest to posttest and
57 second graders had no change in their performance. The older students all improved their scores
58 on this item. This may indicate that this was a slightly harder question for the younger students,
59 or that the students still required some additional scaffolds to fully understand this concept. The
60 cognitive demands of the questions' open-ended nature may have posed differential demands
61 across development as well. These findings align with prior work that suggests genetics content
62 may be particularly difficult for students, but can be best scaffolded, even for younger children
63 with PBL or inquiry instruction (Araz & Sungur, 2007; Henderson & Maguire, 2000; Shaw, Van
64 Horne, Zhang, & Boughman, 2008; Smith & Williams, 2007; Venville, Gribble, & Donovan,
65 2005)

66 Interpreting changes in students' understanding of genes is more difficult, given our
67 findings. Overall, students were no more likely to acknowledge DNA or inheritance in their

68 description of genes following the PBL unit. First and fourth graders demonstrated modest
69 improvements, but we observed no difference in understanding for the third and fifth graders.
70 Interestingly, second graders were less likely to mention heritability following the unit. Notably,
71 this was the case for all second graders rather than being driven by an outlier. Additionally,
72 second graders answered this item similarly to students in other grades before the PBL unit.
73 Since the nature of genes is a common misconception, and since this large drop was only seen
74 among one group of students, it may be the case that instruction outside of the PBL in the second
75 graders' normal classes may have resulted in the presence of a misconception or overemphasis
76 on the connection between genes and traits rather than on heritability. Unfortunately, the
77 research team is unaware of and unsure about what such disruptive instruction may have been.
78 Despite anomalous findings with regard to students' understanding of what genes are,
79 improvements in understanding inheritance following the unit are promising. Even very young
80 students may be capable of learning genetics concepts. We take this as evidence for genetics
81 learning progressions starting earlier than late elementary or middle school. We also take the
82 shift in second grade TAG students – who were engaged in accelerated third grade genetics
83 curriculum outside of the unit – as evidence that students' genetics misconceptions require
84 specific sensitivity in early years.

85 *Arguments constructed in a PBL unit*

86 One aim of this work was to determine if elementary school students are capable of
87 employing reasoning to support claims with evidence in their illustrated products and without
88 explicit instruction about constructing arguments using evidence and reasoning. Students'
89 illustrations and presentation notes as part of a capstone assignment following the PBL unit
90 explicitly incorporated major components of arguments—claims, evidence, and reasoning.

91 Mixed age groups of high achieving and gifted students successfully made claims about their
92 illustrated design solutions and used evidence to support these claims, all without scaffolding or
93 instruction specific to argument construction. The nature and quantity of different combinations
94 of claims, evidence, and reasoning elements varied noticeably across groups in their drawings
95 and written notation.

96 The variation noted across these groups offers further demonstration of a developmental
97 trajectory for students' ability to engage in the coordination activities necessary for the
98 development of scientific arguments argued for by others (Kuhn, 1991, 2005). For learners to
99 improve in their ability to construct higher quality arguments, they must also improve their
100 ability to evaluate their knowledge products using metacognitive abilities (Garcia-Mila &
101 Andersen, 2007). Looking across the groups described in Table 6, those that had a larger share of
102 older students produced richer collections of drawn and written argument components. Thus, our
103 findings agree with other scholars who have argued for the importance of developing
104 metacognitive abilities in complement to enhancing their ability to learn through argumentation
105 (Garcia-Mila & Andersen, 2007; Kuhn, 2005). Following this line of thinking, incorporating
106 instructional elements that afforded students opportunities to explicitly reflect on their design
107 solutions could potentially have increased the groups' explicit coordination of their Markles to
108 the environmental constraints they had. Incorporation of such intentional scaffolding has been
109 shown to be helpful in such learning (Felton, 2004; Zohar & Nemet, 2002).

110 A premise for the current study contends that by allowing students to draw their design
111 solutions, the difference in expectations would facilitate a more accessible venue for elementary
112 students to create high quality arguments. The results developed here do not offer resounding
113 support for this premise in that only one group actually illustrated elements of evidence in its

114 final solution. However, several other groups used their drawings to then generate statements
115 that did incorporate both evidence and reasoning components to explain particular design
116 features. Beyond the drawn design solutions, the presentation notecards also offer further
117 demonstration of student groups explicitly incorporating elements of evidence and reasoning to
118 argue for the design solution they developed. Although students did not express them through
119 drawing, the mode of expression did provide a vehicle for them to incorporate argument
120 components in a coherent manner. Therefore, we agree with scholars who assert that drawings
121 are a valid form for having students express their understanding of complex events (Bowker,
122 2007; Chang, 2012). The current study adds further texture to this notion by demonstrating that
123 although students may not fully express themselves using this mode of expression, drawing can
124 also facilitate students' use of writing in a more meaningful manner. The student groups were
125 prompted through their drawings to explain at minimum their reasoning for including certain
126 design features as well as evidence (environmental constraints) to support their inclusion through
127 written text, both on the image and in their notecards. The use of drawings in the science
128 classroom can assist in helping students express complex ideas through imagery, but also provide
129 an expressive anchor to ground their writing in as well. Yet, the use of drawings does still
130 present challenges in the science classroom.

131 For students, the word "argument" may have a negative connotation, which can influence
132 how students engage in discourse (McNeill, 2009). Rather than ask students to create an
133 argument, we asked students to create an illustrated design solution to assess the presence of
134 claims, evidence, and reasoning. Even though this task differs from typical argument
135 construction tasks, our finding that students have difficulties explicitly connecting evidence to
136 claims is consistent with prior research analyzing students' written arguments (Berland & Reiser,

137 2009; McNeill, 2011; Ryu & Sandoval, 2012). For example, prior to instruction in
138 argumentation, Ryu and Sandoval (2012) rate third- and fourth-grade students' written
139 arguments as having little-to-no evidence cited and lacking explicit justifications. These
140 challenges persisted, although alleviated somewhat, after instruction. In the current study, we
141 also noted students did not explicitly include appropriate evidence in the majority of argument
142 statements they constructed in writing. The persistence of these student challenges provides
143 further support for the emphasis on the scientific and engineering practices identified in the
144 NGSS and state adopted variations of them. Having students engage in these practices is not
145 merely enough, rather we must also help them to understand the nature and role of these
146 practices in science (Ford, 2008; 2015). In light of the results of this study and others noted
147 previously (McNeill, 2011; Ryu & Sandoval, 2012; Venville & Dawson, 2012), we agree with
148 this premise and the importance of incorporating instruction in science classrooms that addresses
149 the practices and their constitutive elements explicitly. Further, if we endeavor to help students
150 gain better understanding and proficiency with arguing from evidence, science educators must
151 also be mindful to help students understand variations in the types of evidence necessary for
152 particular purposes and problems.

153 The instructional unit and related tasks involved in this study were framed using a PBL
154 approach. Often, PBL uses ill-structured problems to frame the entire unit and contextualize the
155 science content to be learned (Savery, 2015). However, the problems students engage in solving
156 are not always answered through empirical investigation. Rather, the end products for students
157 engaged in some PBL units are more aptly characterized as problem solutions. As such, students
158 must come to understand the difference between an empirical investigation and the development
159 of a designed problem solution (Berland, 2013; Householder & Hailey, 2012; Leonard, 2005).

160 To develop solutions to design problems, students must engage in the design process, which
161 includes empirical investigations to test prototypes, but also involves the development of
162 potential solutions that can be used to develop prototypes (Berland, 2013). In this study, the main
163 product of students' efforts reflects this first stage of the design process where they developed
164 markle organisms that could potentially survive in the environmental constraints they collected
165 through their factoid finding work at the beginning of the unit. We argue that in this stage of the
166 design process, material regarding constraints is the most plausible source for external
167 information that can be used to assess the appropriateness for a particular claim or design feature.
168 This information is similar to analyzed data collected during an investigation serving as evidence
169 to support a claim answering the question guiding the investigation. These differences in the
170 nature of information needed for evidence for particular types of tasks can also help explain why
171 we did not see as many evidentiary elements incorporated into student groups' drawn and written
172 markle solutions.

173 The different markle designs from all groups demonstrated that students were mindful of
174 the environmental constraint information they collected, as the features and reasoning statements
175 provided by groups often implied, if not explicitly mentioned, one of the design constraints. It is
176 reasonable to think that if these students had been provided explicit instruction in what the
177 components of a high quality arguments included, particularly in a design solution context, then
178 more groups would have provided explicit connections. The results of this study are promising
179 when interpreted to show that even without such support and guidance intentionally embedded in
180 the PBL unit, several groups did seek out those conceptual connections in the solutions they
181 presented. We concur with other scholars who have also drawn attention to the importance of
182 incorporating explicit teaching in science classrooms that focuses on the unique characteristics

183 and elements of design problems and having students engage in those activities in meaningful
184 ways to help them understand the differences compared to scientific investigations (Berland,
185 2013; Householder & Hailey, 2012).

186 *Considerations for PBL use*

187 The findings of this study can also inform science teachers who work on implementing
188 PBL instruction in their classrooms. As seen in this study, PBL units do create contexts for
189 students to learn complex science content, such as genetics and evolution, as well as getting them
190 to engage in multiple science and engineering practices, such as arguing from evidence. Indeed,
191 these contexts offer teachers opportunities to have students make personal, affective connections
192 with the content they are trying to teach and provide shared experiences of students' participation
193 in those practices, creating space for students to learn from each other. Yet, to engender these
194 types of learning events through PBL, teachers must be mindful of providing explicit instruction
195 in the fundamental nature of the practices. PBL can be used to frame students' engagement in a
196 practice, but to gain a solid understanding of the practice students must also learn about its
197 elements (Ford, 2008). Thus, with respect to the PBL unit in this study, students could have
198 received instruction about what elements are necessary for a high quality argument once they had
199 completed station activity focusing on genetics content and collection of environmental
200 constraint information. Further, this unit could have been enhanced by also helping students
201 understand the broad goal as a design task and the distinct criteria for what claims, evidence, and
202 reasoning entail in such contexts. Explicitly distinguishing the types of argument producing
203 activities (e.g., investigations and design problems) would also enhance students understanding
204 of the variations of activities that comprise the scientific enterprise.

205

206

207 *Limitations & future directions*

208 Despite the benefits of our findings, these are somewhat exploratory and not without
209 limitation. Understanding how illustrations serve as points of assessment and intervention in
210 young children’s argumentation skills should be expanded in future work by employing
211 experimental design and adding instructional scaffolds, such as peer reviews or feedback on
212 students’ labels of claim, evidence, and reasoning in sample illustrations. Because we did not
213 include any scaffolds or probes of student thinking (e.g., peer review or interviews) in this study,
214 our current findings are limited to coding decisions based on our interpretations. While we
215 expect including additional probes would further validate our findings, we were effortful in our
216 current design in order to observe young students’ abilities in constructing arguments without the
217 interference of any instruction. Our findings are further limited in their generalization to a broad
218 population. We examined outcomes with a mixed group of talented-and-gifted and able learner
219 students from one school site. These students participated because they were free to engage in
220 flexible curriculum while other students worked to develop proficiency in math and literacy
221 during a daily enrichment/instructional focus period at the school site. The research questions
222 considered here should be further explored in other populations of students.

223

Conclusion

224 Argumentation is an essential part of both science practice and education, but is
225 challenging for students to learn. This work demonstrated that a different type of task, the
226 creation of illustrated fictitious aliens, when assessed as an argument, shared many features and
227 challenges seen when students engage in typical classroom argumentation tasks. The work here
228 proposes an additional method for teaching and studying elementary school students’

229 argumentation practices and provides evidence of its utility for gaining new insights into how
230 children learn and understand arguments, particularly in a design setting. Students were able to
231 demonstrate success in gaining difficult genetics content knowledge as well as in preparing
232 arguments with, at minimum, two components of well-constructed arguments, and in most cases
233 providing a claim supported by reasoning. This work is informative for understanding student
234 abilities, the potential of PBL, and considerations for its use.

235

236

237

238

239

240

241

242

243

244 **References**

- 245 Allen, D. E., Duch, B. J., & Groh, S. E. (1996). The power of problem-based learning in teaching
246 introductory science courses. *New Directions for Teaching and Learning*, 1996(68), 43–
247 52. <https://doi.org/10.1002/tl.37219966808>
- 248 Araz, G., & Sungur, S. (2007). Effectiveness of problem-based learning on academic
249 performance in genetics. *Biochemistry and Molecular Biology Education*, 35(6), 448-
250 451.
- 251 Baser, D., Ozden, M. Y., & Karaarslan, H. (2017). Collaborative project-based learning: an
252 integrative science and technological education project. *Research in Science &*
253 *Technological Education*, 35(2), 131–148.
254 <https://doi.org/10.1080/02635143.2016.1274723>
- 255 Bell, S. (2010). Project-Based Learning for the 21st Century: Skills for the Future. *The Clearing*
256 *House: A Journal of Educational Strategies, Issues and Ideas*, 83(2), 39–43.
257 <https://doi.org/10.1080/00098650903505415>
- 258 Belland, B. R., Glazewski, K. D., & Richardson, J. C. (2011). Problem-based learning and
259 argumentation: Testing a scaffolding framework to support middle school students’
260 creation of evidence-based arguments. *Instructional Science*, 39(5), 667-694.
- 261 Belland, B. R. (2010). Portraits of middle school students constructing evidence-based
262 arguments during problem-based learning: The impact of computer-based
263 scaffolds. *Educational technology research and Development*, 58(3), 285-309.
- 264 Berland, L. K. (2013). Designing for STEM Integration. *Journal of Pre-College Engineering*
265 *Education Research (J-PEER)*, 3(1). <http://doi.org/10.7771/2157-9288.1078>

- 266 Berland, L. K., & Reiser, B. J. (2009). Making sense of argumentation and explanation. *Science*
267 *Education*, 93(1), 26–55.
- 268 Berland, L. K., Schwarz, C. V., Krist, C., Kenyon, L., Lo, A. S., & Reiser, B. J. (2015).
269 Epistemologies in practice: Making scientific practices meaningful for students. *Journal*
270 *of Research in Science Teaching*.
- 271 Bowker, R. (2007). Children's perceptions and learning about tropical rainforests: An analysis of
272 their drawings. *Environmental Education Research*, 13(1), 75-96.
- 273 Brooks, M. (2009). Drawing, visualisation and young children's exploration of "big ideas".
274 *International Journal of Science Education*, 31(3), 319-341.
275 doi:10.1080/09500690802595771
- 276 Chang, N. (2012). What are the roles that children's drawings play in inquiry of science
277 concepts?. *Early child development and care*, 182(5), 621-637.
- 278 Dentzau, M. (in press). Students' changing mental models of the longleaf pine ecosystem after
279 involvement in an outdoor environmental education program. *Southeastern Naturalist*.
- 280 Dochy, F., Segers, M., Van den Bossche, P., & Gijbels, D. (2003). Effects of problem-based
281 learning: a meta-analysis. *Learning and Instruction*, 13(5), 533–568.
282 [http://doi.org/10.1016/S0959-4752\(02\)00025-7](http://doi.org/10.1016/S0959-4752(02)00025-7)
- 283 Duncan, R. G., & Reiser, B. J. (2007). Reasoning across ontologically distinct levels: Students'
284 understandings of molecular genetics. *Journal of Research in Science Teaching*, 44(7),
285 938-959. doi: 10.1002/tea.20186
- 286 Duncan, R. G., Rogat, A. D., & Yarden, A. (2009). A learning progression for deepening
287 students' understandings of modern genetics across the 5th-10th grades. *Journal of*
288 *Research in Science Teaching*, 46(6), 655-674. doi:10.1002/tea.20312

- 289 Elmesky, R. (2013). Building capacity in understanding foundational biology concepts: A K-12
290 learning progression in genetics informed by research on children's thinking and learning.
291 *Research in Science Education*, 43(3), 1155-1175. doi:10.1007/s11165-012-9286-1
- 292 Felton, M. K. (2004). The development of discourse strategies in adolescent argumentation.
293 *Cognitive Development*, 19(1), 35–52. <http://doi.org/10.1016/j.cogdev.2003.09.001>
- 294 Ferreira, M. & Trudel, A. R. (2012). The Impact of Problem-Based Learning (PBL) on Student
295 Attitudes Toward Science, Problem-Solving Skills, and Sense of Community in the
296 Classroom. *Journal of Classroom Interaction*, 47(1), 23–30.
- 297 Ford, M. (2008). Disciplinary authority and accountability in scientific practice and
298 learning. *Science Education*, 92(3), 404-423.
- 299 Ford, M. (2015). Educational implications of choosing “Practice” to describe science in the Next
300 Generation Science Standards. *Science Education*, 99(6), 1041-1048.
- 301 Gallagher, S. A., Stepien, W. J., Sher, B. T., & Workman, D. (1995). Implementing problem-
302 based learning in science classrooms. *School Science and Mathematics*, 95(3), 136-146.
303 doi:10.1111/j.1949-8594.1995.tb15748.x
- 304 Georgia Department of Education. (2015). *Georgia performance standards*. Retrieved from
305 <https://www.georgiastandards.org>.
- 306 Grooms, J., Enderle, P., & Sampson, V. (2015). Coordinating Scientific Argumentation and the
307 Next Generation Science Standards through Argument Driven Inquiry. *Science Educator*,
308 24(1), 45-50.
- 309 Henderson, B. J., & Maguire, B. T. (2000). Three lay mental models of disease
310 inheritance. *Social Science & Medicine*, 50(2), 293-301.

- 311 Hmelo-Silver, C. E. (2004). Problem-Based Learning: What and How Do Students Learn?
312 *Educational Psychology Review*, 16(3), 235–266.
313 <http://doi.org/10.1023/B:EDPR.0000034022.16470.f3>
- 314 Householder, D. L., & Hailey, C. E. (2012). Incorporating engineering design challenges into
315 STEM courses.
- 316 Kereluik, K., Mishra, P., Fahnoe, C., & Terry, L. (2013). What knowledge is of most worth.
317 *Journal of Digital Learning in Teacher Education*, 29(4), 127–140.
318 [doi:10.1080/21532974.2013.10784716](https://doi.org/10.1080/21532974.2013.10784716)
- 319 Kolodner, J. L., Camp, P. J., Crismond, D., Fasse, B., Gray, J., Holbrook, J., ... Ryan, M. (2003).
320 Problem-Based Learning Meets Case-Based Reasoning in the Middle-School Science
321 Classroom: Putting Learning by Design(tm) Into Practice. *Journal of the Learning
322 Sciences*, 12(4), 495–547. https://doi.org/10.1207/S15327809JLS1204_2
- 323 Kwon, K., Shin, S., Brush, T. A., Glazewski, K. D., Edelberg, T., Park, S. J., ... Alangari, H.
324 (2018). Inquiry learning behaviors captured through screencasts in problem-based
325 learning. *Interactive Learning Environments*, 26(6), 839–855.
326 <https://doi.org/10.1080/10494820.2017.1419496>
- 327 Leonard, M. J. (2005). Examining tensions in a “design for science” activity system: science
328 versus engineering goals and knowledge. *Tidskrift for Lararutbildning och Forskning*
329 [Journal of Research in Teacher Education], 3, 132–146.
- 330 Lewis, D., & Greene, J. (1983). *Your child's drawings: Their hidden meaning*. London:
331 Hutchinson & Co. Ltd.

- 332 Manz, E. (2015). Representing student argumentation as functionally emergent from scientific
333 activity. *Review of Educational Research*, 85(4), 553-590.
334 doi:10.3102/0034654314558490
- 335 McNeill, K. L. (2009). Teachers' use of curriculum to support students in writing scientific
336 arguments to explain phenomena. *Science Education*, 93(2), 233–268.
337 <http://doi.org/10.1002/sce.20294>
- 338 McNeill, K. L. (2011). Elementary students' views of explanation, argumentation, and evidence,
339 and their abilities to construct arguments over the school year. *Journal of Research in*
340 *Science Teaching*, 48(7), 793-823.
- 341 McNeill, K. L., & Krajcik, J. (2006, April). Supporting students' construction of scientific
342 explanation through generic versus context-specific written scaffolds. In *Annual Meeting*
343 *of the American Educational Research Association, San Francisco*.
- 344 McNeill, K. L., & Berland, L. (2017). What is (or should be) scientific evidence use in k-12
345 classrooms?. *Journal of Research in Science Teaching*, 54(5), 672-689.
- 346 National Research Council. (1996). *National Science Education Standards*. Washington, D.C.:
347 The National Academies Press.
- 348 National Research Council. (2007). *Taking Science to School: Learning and Teaching Science in*
349 *Grades K-8*. Washington, D.C.: The National Academies Press.
350 <https://doi.org/10.17226/11625>.
- 351 National Research Council. (2012). *A framework for K-12 science education: Practices,*
352 *crosscutting concepts, and core ideas*. Washington D.C.: The National Academies Press.
- 353 NGSS Lead States. (2013). *Next Generation Science Standards: For States, By States*.
354 Washington, D.C.: The National Academies Press.

- 355 Osborne, J., Erduran, S., & Simon, S. (2004). Enhancing the quality of argumentation in school
356 science. *Journal of Research in Science Teaching*, 41(10), 994–1020.
357 <http://doi.org/10.1002/tea.20035>
- 358 Ryu, S., & Sandoval, W. A. (2012). Improvements to elementary children's epistemic
359 understanding from sustained argumentation. *Science Education*, 96(3), 488–526.
- 360 Sampson, V., & Clark, D. B. (2008). Assessment of the ways students generate arguments in
361 science education: Current perspectives and recommendations for future directions.
362 *Science Education*, 92(3), 447–472. <http://doi.org/10.1002/sce.20276>
- 363 Sampson, V., Enderle, P., & Grooms, J. (2013a). Argumentation in science education. *The*
364 *Science Teacher*, 80(5), 30.
- 365 Sampson, V., Enderle, P., Grooms, J., & Witte, S. (2013b). Writing to learn by learning to write
366 during the school science laboratory: Helping middle and high school students develop
367 argumentative writing skills as they learn core ideas. *Science Education*, 97(5), 643–670.
368 <http://doi.org/10.1002/sce.21069>
- 369 Savery, J. R. (2015). Overview of problem-based learning: Definitions and distinctions. In
370 Walker, A., Leary, H., Hmelo-Silver, C., & Ertmer, P.A. (Eds.), *Essential readings in*
371 *problem-based learning: Exploring and extending the legacy of Howard S. Barrows* (pp.
372 5-15). West Lafayette, Indiana: Purdue University Press.
- 373 Shaw, K. R. M., Van Horne, K., Zhang, H., & Boughman, J. (2008). Essay contest reveals
374 misconceptions of high school students in genetics content. *Genetics*, 178(3), 1157-1168.
- 375 Smith, L. A., & Williams, J. M. (2007). "It's the X and Y thing": Cross-sectional and longitudinal
376 changes in children's understanding of genes. *Research in Science Education*, 37(4), 407-
377 422. doi:10.1007/s11165-006-9033-6

- 378 Springer, K., & Keil, F. C. (1989). On the development of biologically specific beliefs: The case
379 of inheritance. *Child Development*, 60(3), 637-648.
- 380 Stake, R. E. (2006). *Multiple case study analysis*. New York: Guilford Press.
- 381 Thomas, G. V., & Silk, A. M. (1990). *An introduction to the psychology of children's drawings*.
382 New York University Press.
- 383 Venville, G., & Dawson, V. (2012). *The Art of Teaching Science: For middle and secondary*
384 *school*. Allen & Unwin.
- 385 Venville, G., Gribble, S. J., & Donovan, J. (2005). An exploration of young children's
386 understandings of genetics concepts from ontological and epistemological perspectives.
387 *Science Education*, 89(4), 614-633. doi:10.1002/sce.20061
- 388 Voogt, J., & Roblin, N. P. (2012). A comparative analysis of international frameworks for 21st
389 century competences: Implications for national curriculum policies. *Journal of*
390 *Curriculum Studies*, 44(3), 299–321. doi:10.1080/00220272.2012.668938
- 391 Walker, A., Leary, H., Hmelo-Silver, C., & Ertmer, P. A. (Eds.). (2015). *Essential Readings in*
392 *Problem-Based Learning: Exploring and Extending the Legacy of Howard S. Barrows*.
393 West Lafayette, Indiana: Purdue University Press.
- 394 White, R., & Gunstone, R. (1992). Prediction-observation-explanation. In *Probing*
395 *understanding* (pp. 44-64). London: Falmer Press.
- 396 Wirkala, C., & Kuhn, D. (2011). Problem-based learning in K-12 education: Is it effective and
397 how does it achieve its effects? *American Educational Research Journal*, 48(5), 1157–
398 1186.
- 399
400

401
402
403
404
405
406
407
408
409
410
411
412
413
414
415
416
417
418
419
420

Figure Captions

Fig. 1 Mean scores and standard deviations on genetics understanding Questions 1 – 3 at pretest and at posttest. Scores ranged from 0 = no correct conceptual understanding to 4 = mature conceptual understanding. * indicates differences in pretest and posttest scores are significant at the $p < .05$ level.

Fig. 2 Mean change scores from pretest to posttest and standard errors on genetics understanding Questions 1 – 3 across grades 1 through 5. * indicates differences in pretest and posttest scores are significant at the $p < .05$ level.