Chapter 14
How Do Secondary Level Biology Teachers Make Sense of Using Mathematics in Design-Based Lessons About a Biological Process?

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In the fall of 2011 five secondary level biology teachers in the northeast United States implemented an experimental instructional module that challenged their students with a design problem. This challenge required students to perform both mathematical analysis and the engineering application of biological concepts in order to reach a resolution. Specifically, given the parental genotypes of two gecko parents, students were tasked to: (a) mathematically represent the relative frequency of all possible offspring genotypes; and (b) design a systematic breeding program for the geckos that would consistently produce a rare and highly desired genotype as a result. Presented here is a study of how the participating teachers made sense of the mathematics and engineering design applied to the biological process of inheritance, and their reflections on their own implementations of the instructional module. Emergent themes dealt with the limitations of mathematics in teachers' own biology education, their lack of experience with either engineering or design, and their efforts to help students address similar circumstances.

The Organization of This Presentation

A presentation of this study needs some explanatory background in order to be understood by a wide range of readers, and that requires the introductory section to collect and sort a good deal of information from a variety of sources. The first part of this

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section is a review of biology as it is being taught at the secondary level, comparing its characteristics to those of chemistry and physics. This is followed by a description of the policies that will soon profoundly affect science instruction at that level.

For practicing K-12 teachers who no doubt have already begun to contemplate how the latest policies will affect their pedagogy, much of the introductory section serves as an assurance of due diligence on the part of the researchers with regard to practitioner concerns. For others outside the profession, the researchers' intent is for them to consult the introductory material in order to bring themselves "up to speed" with those concerns.

After that, an example response to those concerns is detailed through the content of an experimental instructional module aimed at integrating mathematics and engineering practices with a typical secondary level biology topic. In this section the design challenge that forms the basis of the module is described. It is constructed to require students to draw on their mathematical resources and to make an engineering application of biological concepts in order to arrive at a resolution. Many approaches to a resolution are possible and either competitiveness or collaboration (at the level of individuals, teams, and the entire class) can be emphasized where deemed advantageous by the teacher implementing the module.

Finally, teachers who participated in the study reflect on and react to their implementations of the module in their classrooms and the professional development that informed those implementations. This section concludes with the insights that emerged from teachers' experiences with the module. It is likely that this section and the preceding one will be the ones of most interest and use to K-12 practitioners.

Current State of Secondary Level Mathematics and Biology vis-à-vis One Another

Many secondary school biology teachers are hesitant to put mathematics into service, either as a descriptive method or predictive tool, because topics in any of the sciences at that level are separate and distinct from those in the mathematics classroom down the hall. This is reflected in the lack of mathematics' incorporation in science textbooks (Cantrell & Robinson, 2002).

Furthermore, both mathematics and biology can be taught as a collection of abstractions, without application to observable processes. That is, secondary level biology students can be handed a sequence of well-defined concepts (e.g., DNA, genes, chromosomes) associated with well- defined relationships and processes (e.g., transcription, dominance, random assortment), but no student can actually see any of these without microscopes, so the concepts and processes remain abstract. Meanwhile, the same students encounter similarly well-defined abstractions in their mathematics courses, with no demonstration of these applications to events or objects in their day-to-day lives. The dissociation of mathematics from biology at the secondary level neither indicates what students will likely encounter if they choose to pursue biology as a major or possible career nor promotes how a student's interest in biology could lead to finding engineering or mathematics useful at all.

While not willfully ignored, opportunities for mathematics to be applied to a biology process can easily be neglected. At least in part this is because biology does not afford neatly describable and predictable demonstrations of foundational concepts the way physics and chemistry do. From one organism to the next, "wet" anatomy and physiology might not always appear or behave exactly the same way, and certainly do not perform processes consistently to the same extent that, say, precipitate formation does for chemistry.

This is due to biological processes' stochastic nature being much more evident in class demonstrations than it is for processes in physics and chemistry, and it is related to the amount of conditions that can be observed. If a biology lab could address thousands of parents and offspring, then it would be reasonable to expect students to discover recurrent ratios of genotypes in the offspring, because the large numbers would approximate predictable results. In comparison to chemistry, however, while not every single particle that could form a precipitate will do so, the enormous number of tiny particles that are typically present yield enough of the expected performances so as to render that outcome consistent, predictable, and verifiable from observation.

Likewise, biology labs tend to deal with much larger scales and much smaller samples of observations than do secondary level chemistry and physics. Consider one pair of parent organisms that can have only so many offspring in a semester. Because the parental alleles that are inherited as offspring alleles separate and combine randomly (and there can be tens of thousands of different genes for a species), students can go only so far with determining, recording, and comparing offspring genotypes in that semester. After all, it took Mendel several years and acres of plants before the data he collected yielded their information.

Thus, while useful probabilistic expressions might not spring to mind in chemistry and physics classes at the secondary level, they are entirely appropriate for dealing with the otherwise overwhelming enormity of data associated with combination and permutation in inheritance processes. Unfortunately, if students don't use probability in other science classes, such as physics (that can be linked easily with mathematics), and if they don't encounter probability, permutations, and combinations in a mathematics class, that means biology teachers have to introduce those concepts at the same time they're introducing the inheritance process so that students can get a grasp of the topic. And, if biology teachers do not typically bring mathematics into their classrooms (because mathematics and science are segregated), the extent of the students' grasp is severely curtailed.

Another aspect impeding application of mathematics is the rate at which biology advances can leave gaps between teachers' understanding and the current state of scientific thinking (Cakir & Crawford, 2001). As a consequence, teachers may be inclined to instruct students through memorization of simpler concepts than those being contested in the field. Kleickmann et al. (2013, p. 94) raise the point that, "… the available formal professional development programs tend to consist of short-term workshops that are often fragmented and noncumulative," (referring to a

German study, but generalizing to other countries and citing American studies). Not only that, but if biology teachers try to weave mathematics and engineering and design into their presentations, that effort entails all the additional content knowledge and pedagogical content knowledge that they themselves need to learn, implement, and maintain about those fields. So, if the effect of professional development is questionable within teachers' expected purviews, it seems unreasonable to expect much benefit when the subject matter is unfamiliar, as mathematics and engineering might be unfamiliar to biology teachers.

The current situation is that it is easy to find instructional implementations of engineering in secondary physics and chemistry (e.g., Robinson & Kenny, 2003), and it is easy to find other implementations that apparently do not distinguish one discipline in the sciences from another when introducing mathematics and engineering (Ralston, Hieb, & Rivoli, 2013). Yet secondary level programs focused specifically on biology continue to lack the resources to offer students a range of interesting real-world problems of the sort that actual biologists could address in their professional practice (e.g., modeling the logistics of preserving an endangered sub-species of tiger).

Look at the lessons to be learned from the revival of engineering design in higher education, resulting from years of studies conducted through grants from the National Science Foundation (NSF), with an intensive concentration in the 1980s. There is a reason why engineering professions want people with design skills at the entry level, including research and creative application of scientific principles, and it proved counter-productive for higher education curricula to downplay those skills in favor of other subject matter. If anything, it makes perfect sense to expose such skills to students at the secondary level wherever that can happen, but especially in science courses including biology, in order for them to make an informed choice about careers that might interest them and that they might wish to pursue.

In other words, not only do individual students benefit, but also so do the biology and engineering professions; in the case of the professions the advantage is an influx of people who want to practice in those fields because they are familiar with and perhaps even enjoy what those fields require. Furthermore, early exposure to engineering might lessen the strain on introductory levels of those programs at university, the current popular location for students to resolve whether they have made good career decisions or not (reducing the time and resources students spend as undergraduates when otherwise they would have to start over after concluding that engineering was not a good initial choice for a major).

What Secondary Level Instructional Interventions Will Need to Include

The integration of mathematics with science in P-12 education is currently accelerating toward a critical state of concern for teachers in all science disciplines. This comes as a result of the Next Generation Science Standards (2013, hereinafter

NGSS) resuming where the National Academy of Engineering and National Research Council's (2009) framework left off, that is, in the actual presentation of "crosscutting concepts" (interrelationships among science disciplines) and explicit connections to other subjects in the Common Core State Standards (2011). While updating existing curricula with which they are familiar will be of genuine concern to teachers across the country, there will be the additional complication of addressing engineering concepts and practices, as well (including engineering design), with which most science teachers will not be familiar. Therefore, identifying specific issues that these teachers might face, investigating strategies for mathematics and engineering integration in specific disciplines, and disseminating these strategies at scale and through the literature contributes to the shared effectiveness of all teachers' efforts in this undertaking. But how will this take place?

The Learning Research and Development Center (LRDC) at the University of Pittsburgh launched the Biology Levers Out Of Mathematics (BLOOM) study in order to design and develop instructional modules for both integrating mathematics with secondary level biology and exploiting opportunities for engineering design that had previously lain dormant in the biology classroom. The example of a BLOOM module to be detailed herein presents a design challenge to students and demonstrates where BLOOM can help secondary level biology teachers in using this design challenge in order to get a handle on working with NGSS (2013) performance expectations MS-LS3-2 (middle school) and HS-LS3-2 and HS-LS3-3 (high school):

- Develop and use a model to describe why… sexual reproduction results in offspring with genetic variation…. Emphasis is on using models such as Punnett squares, diagrams, and simulations to describe the cause and effect relationship of gene transmission from parent(s) to offspring and resulting genetic variation.
- Make and defend a claim based on evidence that inheritable genetic variations may result from: new genetic combinations through meiosis…
- Apply concepts of statistics and probability to explain the variation and distribution of expressed traits in a population…. Emphasis is on the use of mathematics to describe the probability of traits as it relates to genetic and environmental factors in the expression of traits.

It will be shown below that the BLOOM module implemented in this study not only addresses these expectations, but in the case of the Punnett square, it also encourages students to replace that cumbersome device with a more sophisticated and powerful mathematical expression, thus incorporating a *crosscutting concept* intended for HS-LS3-3 whereby "algebraic thinking is used to examine scientific data and predict the effect of a change in one variable on another," (NGSS, 2013). In addition, this module emphasizes the *science and engineering practices* for secondary level life sciences of "asking questions and defining problems" and "developing and using models" by requiring students to prepare a presentation about the path they took to their final results. They have to define the sequence of the path and defend it step by step, such that it can be replicated without ambiguity. That justification includes the use of the mathematical expression they develop, while working together as an entire classroom of participants, in order to supersede the Punnett square.

Module Content: Biology–Mathematics Connections Needed for the Design Challenge

Posit a biological process that can be represented by a mathematical expression and furthermore assume that this mathematical expression can be derived from analyzing previous results of the process. Then it is not difficult to manufacture an engineering problem based on manipulating the variables in the expression in order to determine the results, without having to enact the process in actuality.

The BLOOM module presented here addresses inheritance, a biological process that lends itself to mathematical representation through algebraic expression. Consider Mendel's Law of Segregation of Alleles in the case of some animal whose genes each have two alleles; for one of these genes each allele may be either type *A* or type *a*. For this gene alone, each parent could then be one of these genotypes: *AA*, *Aa*, or *aa*. In any of those three possible instances, every parental gamete will contribute one of those two alleles to an offspring. A parent that has *aa* genes will have an *a* in each of its gametes, another parent with an *AA* gene will have an *A* in its gametes, and yet another parent with *Aa* will have either an *A* or an *a* in its gametes.

When applying these principles as an engineer might, one can predict the range of possible outcomes for an offspring having any pair of those parents and determine which of those outcomes, if any, are more likely to occur than others. Furthermore, the prediction of likely proportions of permutations can be extended to multiple genes (the complete genome for any organism being far beyond the convenient range currently served by instruction about the Punnett square).

One trick in applying mathematics to biology is to establish and maintain sensible mapping of biological processes onto mathematical expressions and vice versa. For example, the ratios of expected genotype occurrence in offspring (1/4:2/4:1/4) from a mating of heterozygous parents (both have genotype *Aa*) have meaning for respective allele permutations of *AA*, *Aa*, and *aa* occurring in the offspring. Put another way, when both parents have the same *Aa* genotype, there are likely to be twice as many *Aa* genotypes in their offspring in proportion to either *AA* or *aa*. Or, to present it a third way, given a large enough sample of offspring from these *Aa* parents, one would expect 1/4 to be *AA*, another 1/4 to be *aa*, and the remainder to be *Aa*.

Why? Well, if one starts with the male parent (informally call him "dad" in order to make it easier to keep track) being *Aa* and contributing either one of those alleles to a gamete, with the same being true for the female parent (call her "mom"), that means the offspring genotypes from the combined parental gametes could be:

- *A* from mom and *A* from dad = *AA* for an offspring
- *a* from mom and *a* from dad = *aa* for an offspring
- *A* from mom and a from dad = *Aa* for an offspring
- *A* from mom and *A* from dad = *aA* for an offspring

Except, wait a minute: *Aa* and *aA* are the same. It doesn't matter with which parent the allele originated. So the convention is to label both of them *Aa*, and now it is apparent that there are likely to be twice as many of those as either of the other genotypes.

Detailing the Design Challenge in the Module

For the engineering problem, this BLOOM module presented students with a challenge to detail a breeding plan over several generations of mating for producing rare kinds of geckos, as requested by a fictional zoo (the client). Starting with a given amount of pretended funding, students could "buy" geckos with known genotypes and then breed them to get offspring (neither the parent geckos nor their offspring were real) for which the possible genotypes and the likely ratios of those particular genotypes out of any given set of offspring could be calculated.

Keeping in mind the intended alignment with the NGSS (2013) performance expectation to develop and use a model of gene transmission and variation, one follows directly to the derivation of a mathematical expression that represents the inheritance process and facilitates the sequencing of the breeding plan. But, in order to make those calculations, the students first had to generalize their mathematical expressions to take into account not only any number of genes but also parents with any permutation of alleles.

Ostensibly, this was necessary because the zoo clients had specific criteria for what they would accept, and the criteria involved analysis of parental genotypes and prediction of offspring genotypes for multiple genes simultaneously. In fact, this generalization is related to the NGSS (2013) performance expectation regarding statistics and probability as explanatory vehicles for the variation and distribution of expressed traits in a population.

Once the offspring from a mating were predicted, then students could "sell" them, and use the "profits" to "buy" more expensive geckos with correspondingly more exotic genotypes that could then themselves be bred, producing another round of offspring, and so on until the zoo's criteria for rare animals (expressing some permutation of recessive or incompletely dominant or co-dominant alleles) was met or exceeded.

Say that there are three traits under consideration: size, pigment, and pattern. If the zoo asks for two of those traits to be consistently expressed by recessive genes, then students need to buy whatever common geckos they can afford with their limited initial capital, perhaps setting some funds aside to purchase a particular breeder at greater expense because it is known to have one of the desirable recessive genes. Once they produced true breeders for that expression, that is, parents who could produce only offspring with similar genotypes, students could sell their excess stock (by then including some geckos of greater value than those originally purchased), and reinvest in another breeder known to produce a different recessive expression. This aspect of the challenge is congruent with the NGSS (2013) performance expectation to make an evidence based claim regarding inheritable genetic variations.

Take as a simple example the following: the *A* or *a* allele expresses skin pigment, and *B* or *b* expresses a skin pattern. If a student buys a common gecko male of genotype *AABB* and a female of the more expensive genotype *aaBB* then the student can expect *AaBB* offspring, most of which can be sold for further investment later. But once the student has a female and a male both known to be *AaBB* to breed, that means the offspring from mating them can be expected to be about 1/4 *aaBB* (for which the phenotype is a distinctive lack of skin pigment) which are the more expensive true breeders for the recessive *a* allele. One of them can be kept and the rest sold.

If the student keeps an *aaBB* male and purchases an equally expensive *AAbb* from the profits to date, then it is apparent that all the offspring will be *AaBb.* Mating two of those *AaBb* geckos is likely to produce quite a few common ones (*AABB, AaBB, AABb*, and *AaBb*, no one distinct phenotypically from any other), some true breeders for *a* and some true breeders for *b*, and sooner or later a true breeder for both *a* and *b* (expected phenotype ratios of 9:3:3:1). Over time, the student will create enough true breeders to satisfy the zoo's needs.

Note that there was additional complexity beyond that of manipulating genotypes in that some phenotypes are not associated with one genotype exclusively, and it was necessary for students to determine how to get true breeding genotypes that could produce only similar genotypes in their offspring, thus perpetuating the phenotype, as well. This required a biologically-based distinction among recessiveness and the various kinds of dominance (simple, incomplete, co-dominance) in the relationships of alleles available from each parent. When that was established, the range of expressions possible in the offspring could be calculated.

To students, the apparent intent of the challenge was for them to purposefully breed geckos with known genotypes (or acquire geckos with known genotypes) in order to arrive at a particular genotype acceptable to the zoo, according to a precisely determined plan that they derived themselves, and for which they would need mathematics to predict and keep account of each stage, turning a profit for their efforts. The actual educational intent was for those students to work out for themselves how the laws of combination and expression worked and could be represented mathematically and then manipulated, regardless of the organism involved.

Now, consider that in its appendix devoted to engineering design the NGSS (2013) directs secondary level teachers to provide students with opportunities for:

- Defining the constraints in the problems they face
- Developing multiple iterative solutions by first analyzing complex problems in search of simpler pieces that then can be resolved and synthesized as solutions to the larger challenge
- Establishing criteria for assessing and evaluating trade-offs in the resources they have at their disposal for dealing with their problems

Upon review it may be seen that these are exactly the components of the design challenge.

Some Logistical Aspects of the BLOOM Module: First Appearances to a Teacher

In general, the duration of a BLOOM module can vary between 2 and 4 weeks of daily 45-min classroom sessions. The instructional intent of implementing a BLOOM module is that students must generate and graph data or derive some algebraic expression that describes a biological process and gives them a way to predict outcomes of that process. The module used for this study addressed inheritance.

One of the initial guiding questions for this study was if and how deriving that representation would work with what participating teachers had previously done regarding inheritance, prior to BLOOM. After all, the BLOOM module breaks from tradition for inheritance content presentation in several significant ways:

- Meiosis is not the introductory topic. Instead the BLOOM module starts with fully formed male and female gametes.
- Genotype is treated with little mention of phenotype for three quarters of the module until the concept of phenotype is not only necessary to introduce, with respect to solving the design challenge, but also explicable at last from the genotypic information constructed as a foundation theretofore. This reduces extraneous cognitive load (Sweller, 2011) that would otherwise occur when simultaneously defining both genotype and phenotype while maintaining the distinction of one from the other.
- The Punnett square, a centerpiece of the usual instructional approach, is instead summarily dropped as an unwieldy prediction generating widget that rapidly loses biological meaning in exponential complexity. Instead, students are asked to derive compact and more powerful mathematical expressions.
- Teachers allow students broad leeway to approach a well-defined but ill-structured problem in gecko breeding, as engineers and biologists might encounter. Being ill-structured, the problem has the appearance of being wicked (Rittel & Webber, 1973), and so is a departure from typical problem solving for most students and teachers. Actually, the problem used in the BLOOM implementation is relatively well-defined in order to function less wickedly than what engineers potentially encounter, and instead acts more in the manner of a puzzle, for which there are several ways for the pieces to be assembled but only a finite range of so many pieces and their beginning and end states. Yet it is not a familiar textbook biology problem by any means.

Research Questions about Biology Teachers Using Mathematics and Engineering

This paper's focus is not primarily any of the module's instructional effects. Instead, this investigation concerns how a number of individual biology teachers made sense of the BLOOM module that was being iteratively developed through rapid prototyping and then implemented in their classrooms. Cox (2009) describes the path that novel subject matter takes in higher education, from initial agreement among faculty about definitions for the subject matter to final legitimization as explicitly advertised subject matter in a course catalog; there was a similar process at work with the BLOOM module. An initial agreement about what mathematics expression was appropriate for mapping inheritance had to be negotiated among the BLOOM developers and presented to the participating biology teachers during their professional development and subsequent classroom implementation. These teachers presented the interplay between mathematics and inheritance to their students, and both teacher and student reactions tempered what the BLOOM developers kept and modified in subsequent iterations of the module. In this way, it was discovered what applications of mathematics and what presentations of the mathematics proved robust enough to not only survive confrontation with teachers' and students' biology understandings, but also to augment those understandings.

Of additional importance, observation of teacher efforts was not limited to resolution of only the mathematic content knowledge required for the modules (representing a legitimization of mathematics' place in biology content). What this study also attended to were any shifts in teachers' pedagogical content knowledge (Ball, Thames, & Phelps, 2008; Davis & Krajcik, 2005; Shulman, 1986) as those occurred during the practice of teaching biology through mathematical applications.

Finally, as previously mentioned, the emphasis on mathematics was complexified with an introduction of engineering concepts and practices, and how those affected content knowledge and pedagogical content knowledge were observed, as well.

How did biology teachers describe what happened in their classrooms during their implementation of the BLOOM study instructional material? How did the focused use of mathematics affect the nature or extent of their individual pedagogical resources and their use of those resources for teaching biology?

Unit of Analysis and Anticipated Critical Dimensions of Phenomena

Although Elmore (1996, p. 16) was not involved with this study, his characterization of teachers who maintain "ambitious and challenging practice in classrooms" pertains nicely to our participants as teachers who are "motivated to question their practice on a fundamental level and look to outside models to improve teaching and learning." As the study's unit of analysis, there were five participating teachers, with each having one or two daily sections of a secondary level biology course (ranging from grades nine through twelve), and each section consisting of from 10 to 25 students, depending on absenteeism. Because the BLOOM module was being developed in a rapid prototyping manner, making it available every semester over the year to date, three of these teachers had also participated in previous implementation rounds. The other two were newly recruited in an effort to expand BLOOM implementations within the same geographical area (participants represented public school districts and parochial schools in the northeast United States). All participating teachers were female in this round.

During this study, participants met as a group only three times, for about 3 h each time, first at one professional development session before the implementation started and then another during the implementation, with a reflection session after the implementation had concluded. Contact time was thus a critical dimension that affected what participants could achieve as a group.

A further critical dimension of the implementation was that of the difference between intended and enacted duration of the module. While the BLOOM project team considered the module to require a 2–3 weeks implementation schedule, various factors dragged this out to from 4 to 5 weeks in the field. In addition to interruptions at each school from conflicting events that had been set months beforehand, including standardized testing, there were unpredictable amounts of time required for students to reach conclusions on their own as the module materials encouraged teachers to do.

Methodology

This study involves an empirical approach to gather phenomenological data, relying heavily on: observation of the participants encountering the BLOOM module in professional development sessions; observations of participants implementing the BLOOM module in their classrooms; and interviews with participants immediately after their class sessions, as well as two delayed interviews afterward. These last two interviews contributed the most data to this study.

Although Rossman and Rallis (2003, p. 98, citing Seidman, 1998) describe a phenomenological sequence of interview as having three components, it was prudent here to combine the first two into one longer interview with each participant, covering both the professional history and the implementation of the BLOOM module (see Appendix A). This corresponds to a naïve description as detailed in Moustakas (1994, pp. 13–15, citing Giorgi, 1979, 1985), an anecdote or narrative that a participant living the experience (i.e., teacher enacting an implementation, in this study) tells about the experience, a recounting of events without delving for explanation or justification.

The second interview (see Appendix B) was then devoted to a dialog between the BLOOM developer and each participant, regarding the participant's individual reflections and interpretation of the implementation. In order to facilitate the crucial act of triangulation known as member-checking (Lincoln & Guba, 1985), each participant was presented with the data analysis relative to her interviews and observations and asked to interrogate the researcher's interpretations, especially those which rang false or unconvincing. This is where the previously empirical orientation of data collection and analysis explicitly gives way to a heuristic manner, in what van Manen (1997, p. 99) characterizes as the hermeneutic conversation where the researcher and participant tackle the question, returning theme by theme to ask again and again, "Is this what the experience is really like?"

Data Analysis

The teachers participating in this implementation did not regularly convene as a group, having only three professional development sessions as described under the previous heading of *Unit of analysis and anticipated critical dimensions of phenomena*. On one hand, these sessions were purposefully structured improvements over the typical format as described by Kleickmann et al. (2013, p. 94, "short-term workshops that are often fragmented and noncumulative"), including a post-implementation meeting (p. 92, "Several studies suggest that teaching experience needs to be coupled with thoughtful reflection on instructional practice, with non-formal learning through interactions with colleagues, and with deliberative formal learning opportunities."). On the other, participants did not attempt to discuss ongoing implementations with one another outside of professional development sessions, engendering little in the way of community. As a consequence, each of the participating teachers will be discussed in turn as an individual. In order to maintain their confidentiality, each has been assigned a pseudonym: Alice, Betty, Carol, Dorothy, and Emma.

Alice Would Have Liked to See More Math Years Ago

Alice teaches in a parochial school that, while not inner city, occupies a neighborhood of older wood framed homes built cheek by jowl, dotted with factories and warehouses succumbing to dilapidation, and laced throughout with a maze of meandering streets. She has participated in previous implementations of the module, and is familiar with the changes that have accompanied the iterations. She also has the most experience in the classroom of all the participants, so her reaction to the module's increasing sophistication is of great interest, in that her naïve description of any implementation has likely given way to repeated reflection long before this study, and whatever sense she is going to make of it has already been accomplished.

It is possible that hers is the transition described by Drake and Sherin (2009) whereby only after repeated usage of materials, can teachers establish the level of trust they place in the designer's intent and the materials' utility, as opposed to the initial confrontation when affordances and constraints still need to be discovered. Indeed, Alice made a point of listing what particulars from the BLOOM module she intended to incorporate in her future presentation of inheritance, including leaving meiosis for the conclusion.

For her, mathematics is a medium necessary for analysis and presentation of data, and there clearly is not enough of it in general biology today. She is one of the participants who has consistently maintained Elmore's (1996, p. 16) "ambitious and challenging practice in classrooms" and motivation "to question their [own] practice on a fundamental level and look to outside models to improve teaching and learning." She said in this study's first interview that, "A teacher has to be open to seeing differently or kids won't look at [content] another way." Thus, when the BLOOM study first recruited her to work with a mathematically intensive module, she responded enthusiastically.

As with all of BLOOM's participants, her attitude is in direct contradiction to her own biology education in secondary school, where mathematics dared not speak its name. In the secondary level biology classes that she took as a student, genetics was ignored. However, she did not follow a direct path to becoming a biology teacher, in that she first chose a related field for her initial teaching practice and then returned to university some years later.

By then, biochemistry had been introduced into the curriculum. For her, the place of mathematics in biology was to be taken for granted from that time on, and she believes that more biochemistry and its accompanying mathematics is needed in the biology curriculum where she teaches. Likewise, any preparation for physiology studies must include mathematics because "everything for physiology has an equation."

On one hand, Alice's lack of exposure to mathematics at her own secondary level of biology parallels that of all our participants, as will be shown. On the other, her experience at university seems to differ significantly from that of the other participants, so the insight to be gained from her interview probably is not going to be entirely the same as for the other participants. This is evident in other aspects, as well; consider her answer to a question about textbooks, to the effect that the one she is using provides a graphing exercise for each of its numerous labs, something she has emphasized in other responses as being crucial for biology students to practice. No other participant gave more than a brief dismissal regarding the state of the textbook in use (note that the textbook publisher varies from school to school in this study). Was she actively looking for affordances that others had already quit trying to find?

Betty Will Not Give Up on Her Students' Exposure to Mathematics

Betty teaches at a public school that might not exactly be run down, but certainly has been used roughly for many years and shows its age. Student absenteeism is much worse there than at any of the other participants' schools, and this disrupts attempts at team-based projects such as those in the BLOOM module. Betty does her best to shift students from team to team in order to make progress every day, and has implemented several versions of the module previously, but still finds her students taking more weeks to get done than those of other participants.

It is likely her conscientiousness about reaching every student that slows her down. In response to the absenteeism, she is determined that, when a student actually does decide to show up he or she will be brought along to the level of those in attendance every day.

Although Betty is an experienced teacher here, she is still dealing with the cultural differences in this setting compared to the student/teacher model of relationship she grew up with in her native country. With regard to the apparent grudging respect she gets from the students, she feels that innovations such as the BLOOM module, that places the responsibility for research and discovery of knowledge needed to grasp the content squarely on the student, are paths worth exploring in order to engage her classes.

Unlike most of the other participants, her secondary level education explicitly addressed the mathematics with which biology teachers should be equipped. There was no hesitation on her part in dealing with that aspect of the module. She and Alice actually addressed the design challenge together during the professional development, and they seemed to follow the derivation of the mathematical expression with little instruction.

Among the participants it was also this pair who first attended to multiple genes in each parent as they set about sequencing the breeding for the design challenge. This is not to say that the BLOOM module's exclusive focus in its initial phases on genotype aligned with Betty's strategies of how genotype/phenotype interaction should be taught, but rather that she was willing to deal with the potential for cognitive discomfort on the part of her students in order to discover any possibly beneficial effects from the module's implementation.

She was keen to find any increase in evidence-based generalization and inductive reasoning among her students, especially involving the use of analogies in order to transfer inheritance concepts to something other than geckos. She was persistent in finding and making opportunities for students to phrase their biology questions as comparisons to topics they already knew, and this practice predates her work with BLOOM. For example, when interviewed for the first time, she had just that morning led her students through the similarities of compound interest (familiar to some students, and generally engaging due to its financial nature) and calculating population growth.

But in order to get to that stage, Betty sees at least two prominent obstacles: segregation of subjects; and level of expertise perceived necessary. In the former, students have been conditioned to expect rigid and impervious boundaries between subjects, such that the mention of mathematics in a biology class is an intrusive anomaly. In the latter, students have not had to formulate mathematical expressions in service of their own problems, and so expect that only a mathematician would have the expertise to do so. Simply because the BLOOM module attacks those misconceptions does not ensure that students will either embrace an integration of mathematical subject matter with that of biology or attempt what they had previously classified as exclusively expert behavior and beyond their abilities.

Carol Was Wary of the Mathematics at First

Carol's school is one of recent vintage, and situated on its own campus just outside a commercial strip of its suburban community. Easy going and affable, Carol also participated in the various versions of the BLOOM module, and developed a forthright attitude in dealing with the BLOOM researchers, which they encouraged. From time to time, she augmented the BLOOM materials with worksheets and information that she felt her students needed, but this decreased with each iteration, either due to her concerns being addressed from one version to the next or perhaps attributable to her increasing trust in the materials.

Carol does not have any issues with the mathematics (algebra and probability) itself, but was not always confident about the extent to which she resorted to it in the past, as when she asked in the first interview, "Is measurement math?" Likewise, she does not object to exploiting opportunities for mathematics in her teaching. But she is very careful to watch for students "getting lost in the math," because the integration of the two subjects is an uncommon occurrence for them to face, and she feels that not everyone can handle that. Of course, "nobody pushes cross curriculum" at her school at any level (individual teachers, departments, administration), and unless the state's impending biology standards do, it is unforeseeable that anyone will.

She speaks of mathematics as an "enhancement," perhaps for those "math-oriented" students who need a challenge beyond the day-to-day biology content, and often introduces her opinions about mathematics' place in biology with caveats. For example, in response to the National Research Council's (NRC, 2012, p. 64) statement about mathematics' dual communicative and structural functions, she begins, "*If the student is able to handle math* to make logical deductions, then it is a wonderful tool to explain biology." [emphasis added] When she does entertain the use of mathematics in an assessment item, it is only with her "advanced kids."

It is not surprising that Carol would adopt this prudent wariness. She is an experienced teacher and no doubt has seen a highly touted reform or two run its course and vanish. Nor does her own background as a student give her any compelling reason to throw in with the BLOOM module before it has proven itself to her satisfaction. She does not recall "math pushing me" or any intensive concentration on mathematics over the period from her secondary level biology courses through university and on into pre-service teaching. Furthermore, the textbooks she works with currently provide no such emphasis.

Prior to the BLOOM module, the Punnett square performed adequately as her touchstone for inheritance related mathematics. "We have this grid that can show you real easy what these combinations are." Oddly enough, her observation about deriving a general mathematical expression to replace the Punnett square was that the "denominator [of the expression] slowed you down when it wasn't 16," that is, when at least one parent was not heterozygous for two alleles. This raises the question of whether it really was easier for students to use the Punnett square when the denominator was 16 (a dihybrid cross) as opposed to the general expression.

This particular situation, often depicted as the cross of two parents *AaBb* × *AaBb*, is a well known litmus test that separates mechanistic or intuitive approaches from precise calculational ones when generalizing from one gene to dealing with two or more genes (Moll & Allen, 1987; Tolman, 1982). Were the students who were slowed down by the general expression neglecting to attend to the biological process in order to focus on mathematics, or did getting the math to work bring biology any more into focus for them than plugging allele designations into the Punnett square?

In fact, Carol had already developed another approach to the Punnett square on her own, that enabled students to make the transition from one gene to two and even three or more. She first had them isolate the Punnett square for each individual gene, producing however many two by two squares as there were genes. Then, in each quadrant of the first gene's grid, a second gene's entire grid was inserted. The results in each subdivided unit of the first gene all have the same alleles from the first gene but vary by the alleles of the second gene (as shown in Fig. 14.1). So, from a pair of 2×2 grids a third grid emerges as 4×4, with 16 units total. If one then inserts another 2×2 grid, for gene *Cc*, say, into each unit of the 4×4 grid, the result is a subdivision of each of those 16 units into 4 new units, such that an 8×8 grid emerges, with 64 units total, all of which have two alleles from each of the three genes.

This approach had occurred to the BLOOM developers, as well. On one hand, the Punnett square is not robust enough to withstand accounting errors, and it might help students that this technique makes it difficult to fill in the grid incorrectly. On the other hand, the formation of parental gametes that would appear at the heads of rows and columns in the typical Punnett square is ignored, thereby deleting one of its actual redeeming features. Furthermore, the acreage required to accommodate generating the permutations of multiple genes burgeons just as rapidly in Carol's approach to Punnett squares as in any other, no matter how accurate one is about keeping track of them all. Upon reflection, Carol seemed satisfied that her implementation of the BLOOM module had in fact exceeded the limitations of the Punnett square as it is typically constructed.

Given all that, Carol was still only tentatively in favor of the BLOOM module's mathematical emphasis. While she felt that such aspects as calculating increasing dollar values for correspondingly rarer gecko offspring indicated an acquaintance with inheritance, she was not happy with the ambiguity of topics that eluded resolution, as in whether there were three or four different products of a monohybrid cross (genotypic *AA, Aa, aa* versus algebraic *AA, Aa, aA, AA*). In addition she would like to extend the use of the manipulables into a modeling of meiosis, rather than setting them aside at that crucial phase. She also discussed how earlier versions of the BLOOM module defined the target genotype and phenotype more explicitly and were better suited for classes with lower abilities. She intended to implement both earlier and later versions of the module in the future, with her honors classes getting the later version.

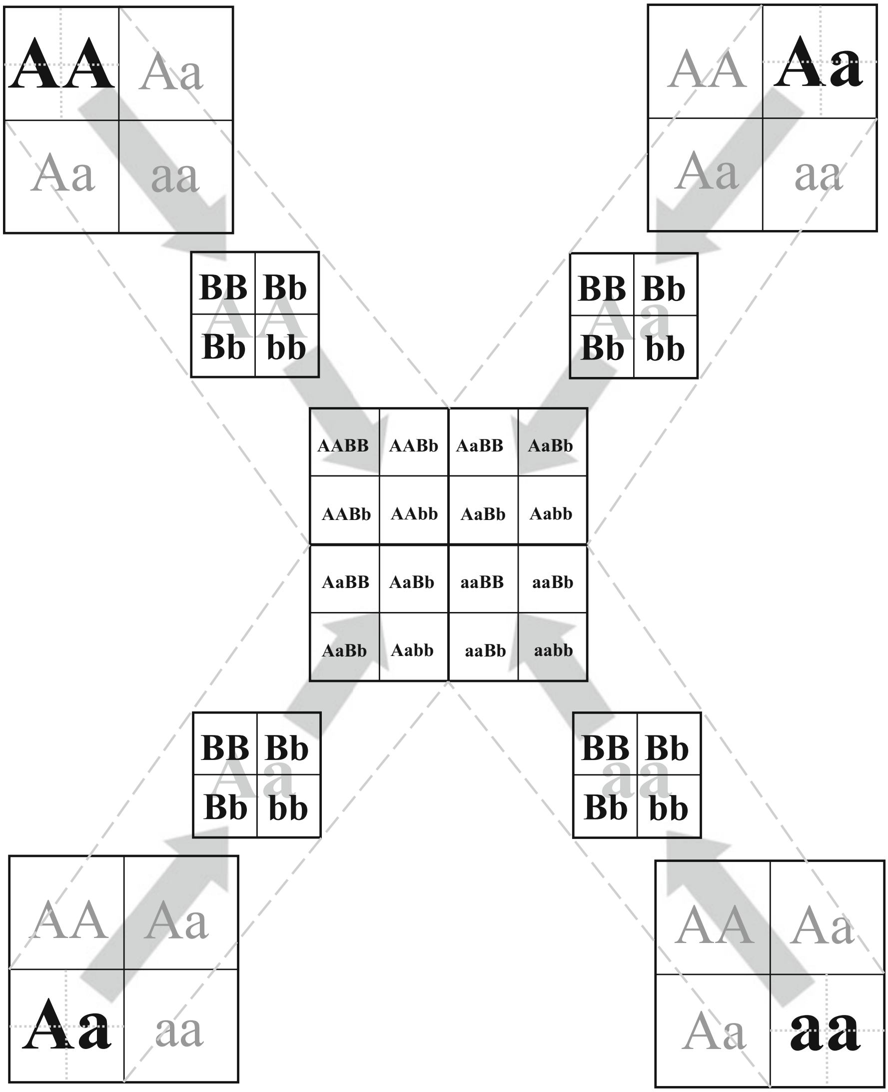

Fig. 14.1 Carol's Approach for permutations of more than one gene: Consider Punnett square for each gene by itself, insert the entire Punnett square for another gene into each unit of the first, subdividing it (here the entire Punnett square for Bb × Bb is inserted into each unit of the Punnett square for Aa × Aa)

Dorothy Emphasizes the Mathematically Rigorous Aspects of Statistics When She Can

Dorothy's suburban parochial school alone boasts a sealed concrete floor finish and the modern exposed roof deck and ductwork in lieu of a ceiling tile grid. Certainly, the equipment in her room has met the least suffering at student hands, and her current charges are not ones to leave a lab area in tatters by any means. While there is no doubt who is in charge of the classroom, the atmosphere is almost collegial with give-and-take as she engages her small groups of 15 or so students.

Her orientation to biology teaching is pronouncedly more quantitative than that of other participants, and it is clear that she is familiar with statistical methods of analysis and their terminology. Regarding the opportunity to show students what biologists actually do, she says, "Real researchers have tests," elaborating on this to implicate measurement, comparison, and statistical significance as components of answers to research questions in a biology course. "Every time a student does an experiment there is a statistical test," is how she describes the honors students' work. Although she is not yet this rigorous with her lower level students, she wants this to be more the case for all of her biology classes.

But Dorothy's own secondary level biology involved no mathematics. And it was not until she was working on a thesis at university that she needed statistics; it just was not necessary for weekly lab reports. Concluding that it requires her initiative to bring mathematics into the secondary biology classroom, she not only helps her regular students with statistics, but also participates in summer workshops that focus on that subject matter.

Responding to the enormous scope of student interests in research has helped her work past a common subterfuge that teachers adopt when confronted with a situation about which they are ill informed. "I'm not gonna lose control if I reveal I'm not sure what to do next," means that she and a student seeking an answer need to plan together how to find one, and modeling that planning is another opportunity to demonstrate what biologists face in practice. Unfortunately, the current selection of textbooks does not aid in that pursuit. Or, as she says, "Even when they have that little page [inset or sidebar; exactly the point made by Cantrell and Robinson (2002)], they don't go into detail."

Her participation in BLOOM was thus part of her active search to find teacher materials to support this effort. She has always gone beyond the limitations of the Punnett square in her classes, drawing sperm and eggs and filling in allele letters rather than just labeling rows and columns in the grid, and her quest for an easier way to predict inheritance made the BLOOM module attractive. What she discovered, however, in reviewing student work for the module was that aversion to mathematics (in favor of a visually oriented technique) reinforced use of the Punnett square, rather than replaced it, when students were given a choice.

Dorothy is facing a dilemma similar to that of undergraduate engineering education in the 1980s, when the engineering professions instigated NSF studies into the absence of design in curricula, and now Dorothy's administration is getting pressure from alumni of her school about incorporating more problem solving. But, while Dorothy currently intends to implement the BLOOM module or a modification of it with her classes next year, that is a decision attributable more to student preference than to administrative advice. The module is much more student directed than the way she normally teaches, and that novelty is an important consideration for her in developing student engagement.

Her candid evaluation is that the BLOOM materials' inadequacy (to make a mathematical alternative to a Punnett square seem attractive) is in part due to the confusing quality of the directions and examples. She herself was sometimes unsure about when an example was being presented. However, by the second professional development session, she felt confident that she was in command of the module.

Emma Is Concerned that Introducing Mathematics Reduces the Focus on Biology

Emma's parochial school sits squarely in a residential suburban area. Considering all of the participants' classrooms, hers is the most densely packed with models and living animals and relics of bygone projects. Whether feigning or sincere, her students are consistently vocal about their disdain for the BLOOM module, yet some of them have demonstrated dramatically beneficial effects.

This was the case with Melissa (not her real name). As Emma relates, "In the beginning they were shutting down … and Melissa, that's her nature. She likes things the way they've always been." Indeed, Melissa had not been participating much at all throughout the first part of the module's implementation, when at the start of class 1 day, she started to weep to the extent that Emma was obliged to remove her from the classroom, requesting another teacher to monitor the class in the meantime. "She really struggles with things that are uncertain and not secure," was Emma's comment in the post-class interview that day. Melissa kept trying, though, and when the class was reviewing the charts that they were preparing to post about two-gene system combinations, she actually spoke up in her group; another student asked about how many combinations they should get, and Melissa set him straight on how many he had found and how many she had found.

Melissa then worked through a Punnett square that she had modified from a four-by-four grid in response to there being fewer combinations from homozygous parents than from a dihybrid cross. The discovery that she could change the square led her to interrogate how it could be made less complicated in order to serve a three-gene system. First it occurred to her that a three-gene Punnett square was going to have $(2\times2\times2)\times(2\times2\times2)=64$ boxes to fill in, and that was something her group had not considered. When another student asked if they had made an accounting mistake, Melissa was ready to take charge. "Yes, I'll work on that," was soon followed by, "There! I fixed everything," an entirely reversed role from the student who had been led in tears from the room only a week or so before.

It may be that Emma's approach to pedagogical content knowledge has enabled her to adopt novel strategies more easily than other teachers can, leading to this sort of result. Although well grounded in content knowledge from her previous practical experience in a biology laboratory setting, she never formally learned to teach biology. In determining the details for her curriculum, she went through the textbook provided from her school and focused on topics that she thought would be interesting, at no time beholden to the reification of a standardized testing agenda that plagues teachers in the public schools. If not altogether laissez-faire, her philosophy is robust enough to tolerate significant change from 1 year to the next.

Of course, if mathematics was never an emphasis in her secondary biology or university courses (as was the case), and if the biology textbook she was perusing did not discuss mathematics applications (as was also the case), then there was no reason for her to introduce mathematics merely for the sake of novelty either. Thus, until the BLOOM module implementation, she did not plan to use any mathematics in her classes other than the Hardy- Weinberg equilibrium. She scheduled the Punnett square's annual appearance, demonstrated its traditional service as a widget for the presentation of offspring possibilities resulting from a dihybrid cross, and then ushered it from the stage without students explicitly examining its mathematical aspects. Emma even stopped offering extra credit for extending a Punnett square to four genes because only those students who were mathematically adept attempted it, apparently without beneficial effect to their understanding of inheritance as a biological process.

This does not mean that the BLOOM module was an unmixed blessing as far as clarifying advantages from mathematical applications. Instead, Emma felt that the amount and concentration of effort toward developing a mathematical expression for genotype proportions obscured the underlying reason for expending that effort to begin with. While using the Punnett square is simulative without being emulative of inheritance processes (i.e., simulative in that Punnett squares imitate content by generating allele permutations, but not emulative in that they do not imitate the processes of gametes combining that produce these permutations, per Moulton & Kosslyn, 2009; Stewart, 1982 makes a similar case without using that particular terminology), in essence ignoring the biology, it is also just plain easier to memorize for a couple of genes than deriving and grounding a generalized process, diverting attention from the biology. Her suspicion in this regard was borne out in an assessment item following the implementation, wherein she asked students for results that could have been determined from either a Punnett square or the mathematical expression they had recently derived; the majority chose the Punnett square.

Coding and Themes

Clearly, one code that all the participants shared explicitly was the absence from their backgrounds of mathematical expressions for biology. Had the participants been entirely middle school teachers this would not have been unexpected; Kuenzi

(2008, p. 10), citing a Congressional Research Service analysis of the School and Staffing Survey, reports, "Among middle-school teachers, 51.5 % of those who taught math and 40.0 % of those who taught science did not have a major or minor in these subjects." But there were high school teachers who participated in BLOOM, as well, and their mathematics backgrounds were similarly thin, and that does not correspond with the national survey data.

It is not that the mathematics was unavailable to the teachers, but that it was not stressed as an application to biology for them either at the secondary level or university, unless in the service of a capstone research project or the overlap between biology and chemistry. This appears to be a contextual code, describing a situation that participants accept as historically emic for themselves as biology teachers, but to which they now can only react, rather than affect, due to its nature as a fait accompli.

Two major kinds of these reactions needed to be coded. One appears in Carol's reflection about the difficulties of taking on the mathematics integration by herself:

> It's very hard for an individual teacher to get where [BLOOM] got me, and I think that's a frustrating aspect from teachers. It's not so much that we don't want to put in the math, but kind of like what you said, I seemed like I had to be convinced this would work. In a sense I do, because I need someone to provide that with me, 'cause it's not something that's been given to me ever before, and I need to see it happen in the classroom. But I can't create something that I don't even know about. …I was very amazed at the [previous version of the module], and thought, "Oh my gosh, I wish I had a team of five people working on a project for me for next month." Like, that's how much needs to go into something like that, and I think that's another reason why teachers are hesitant … y'know, you're gonna' get a biology textbook with worksheets and transparencies, that's what you're gonna' get. I don't have any way to incorporate math, unless it's my own creation with no background, and no [professional development], y'know, nothing.

Emma provides a similar view:

> In the science classroom, having to teach so much content in a short amount of time, I think trying to find a way to incorporate the math – on my own – is just a bigger challenge for me at this point. I've only been teaching for five years, so maybe I'm still trying to learn how to teach the science content? … This is probably my first year that I actually feel comfortable that I don't have to keep developing things. Y'know, the things that I've already developed have been working. I'm just kind of tweaking things here and there. I might be able to incorporate math here or there in something in my tweaking for future use, but to start from scratch and develop a whole unit or a whole lesson that does incorporate the math? I'd probably say, no, I wouldn't.

Without BLOOM, the integration of mathematics and biology would rest on participants' shoulders alone, because they couldn't expect any buy-in from the mathematics departments or administrations at their schools. Collaboration might still get plenty of lip service, but its implementation rarely occurs. As a result, coding also involved participants' recognition of limitations.

Theme: Interpreting an Unprecedented Emphasis on Mathematics as Instructional Improvement

The other major reaction is, of course, taking the next step after one decides that something needs to be done, but that the something is beyond one's individual resources. Less verbally explicit, it is instead operationalized by partaking in research that doesn't just passively recognize the absence of mathematics, but actively promotes mathematical expression as description and application of biological processes. While there lingered a hesitance among some participants to implicate mathematics directly, problem solving seemed an acceptable way to frame modifications to biology content. From their point of view, even those of their students who were visually-oriented could solve a problem, but only those who were mathematically- oriented could solve a problem mathematically.

The qualities of integrating mathematics and biology dealt with so far run along a continuum of participants' beliefs that mathematics can be beneficial to students in their biology classes: recall of a mathematical absence in their own biological education, perception of that continued absence (to varying extents) in their own teaching, their realization of an inability to address the absence individually, and their decision to participate in research that provides them with one example of how to deal with that absence.

The theme of becoming an expert teacher is evident, of course, but this is tempered somewhat for the public school teachers. Even though increasing student sophistication in problem solving is an acceptable enough goal for the parochial school teachers, there is further conflict to be resolved in the public schools with how problem solving applies to standardized testing.

Both parochial and public school teacher participants saw their higher level students struggle with having to work through the perceived ambiguities of the biology content. Likewise, most of these teachers also observed noticeably more participation than was typical from their lower level students, as a mathematical expression was derived through whole class negotiation. Carol described it as students leaning on each other for details during the implementation, but walking away with the big ideas. This is the basis for lifelong learning, in that recalling the specific content is not as important as the belief in one's ability to purposefully construct the content from available information when needed. She had also previously noted:

> I think too many times we do stuff with the kids, and don't reflect on it; and then they don't really know why they did it … I'm taking advantage of the structure that you have already provided to me and using the time to reflect and hear how people are thinking …' cause I think the ultimate goal anymore is, "learn how you think," evaluate your thinking, and I heard you guys say that someone was stressing that even; I mean, that's, that's what's kind of been pounded in teachers lately; the twenty-first century…

This merely highlights the conflict that public school teachers expect to arise from BLOOM versus standardized testing's format emphasizing the recall of details, to which parochial schools are not beholden (even though many actually do participate in standardized testing in order to provide a benchmark for their students' academic performance).

That noted, the National Board for Professional Teaching Standards (2012) does report a correlation for students having National Board Certified teachers (i.e., teachers seeking to increase their expertise, as the participants here are doing) and those students' higher scoring performance on standardized tests. Therefore, the question of how that conflict actually affects students is in need of further scrutiny.

Theme: Teachers Resolving Ambiguity for Themselves and in Preparation for Helping Their Students

A second theme was one of recognizing and dealing with contestability in biology content, at first apprehended as ambiguity by both participating teachers and their students. An example is that of the monohybrid cross discussed previously, where both parents are heterozygous, having a dominant and recessive allele, say *Aa*. Algebraically, there are four possible offspring genotypes: *AA, Aa, aA*, and *aa*. Genotypically, there are three: *AA, Aa*, and *aa*. This is so because *Aa* is indistinguishable from *aA* (most of the time, with this disclaimer: considering only one gene, an offspring having an A from mom and an *a* from dad is exactly the same as another having an *A* from dad and an *a* from mom, unless imprinting is involved, and the topic of imprinting, while correct, introduces complexity of limited utility at this level).

However, because there are twice as many *Aa* as either *AA* or *aa* the difference in relative ratios is not trivial, whether in a mathematical expression dealing with allelic permutations in the offspring from a single parental pair (especially when considering multiple genes) or in the subsequent generations for a much larger population.

The point is: there are reasons to consider both views, and it depends on the circumstances as to which of those views is relevant. Furthermore, this point is not peculiar to genotypes (e.g., *Aa* versus *aA*), or even to genotypes as those relate to phenotypes (because genotypically similar *Aa* and *aA* not only express the same trait phenotypically, but also share that phenotype with genotypically dissimilar *AA*), extending throughout biology and beyond. As Bruner, Goodnow, and Austin (1956), state:

> Do such categories as tomatoes, lions, snobs, atoms, and mammalia exist? In so far as they have been invented and found applicable to instances of nature, they do. They exist as inventions, not as discoveries. (p. 7)

It is easy to see that there are any number of biological constructs, such as taxonomy and speciation, that are not universally settled, making much of biology a wicked problem (Rittel & Webber, 1973) in the truest sense of the term.

Indeed, the BLOOM design challenge was purposefully contrived in order to require students to confront and define a concept of rarity and what that meant in various contexts. For example, what rarity means to a zoo administration capable of breeding a special gecko that is genetically consistent generation after generation, must be very different from what rarity means to the rest of the world in which such a special gecko does not even appear. For the zoo administration the special gecko is disproportionately small with respect to the population of geckos overall, while at the same time being incapable of reproducing any other genotype. To the rest of the world, the artificially selective breeding that resulted in this special gecko could not have occurred otherwise, thus confining this special gecko to a singularity that excites disproportionate curiosity. To gecko collectors and breeders who recognize the time and expense involved in the breeding sequence, the special gecko represents a disproportionate value exceeding that of geckos they have already encountered.

This theme of recognizing and dealing with contestability in biology content indicated teachers' efforts at coming to grips with how to support their students' comparisons of contexts in which to locate and develop views regarding biological constructs. When teachers can impel students to deal with problems for which the context is not immutable and thus must be established by the student, it stands to reason that students' self-efficacy improves as a result (at least with respect to these kinds of problems).

This has a profound effect on the models that students use in order to understand biological processes, and what teachers should expect when eliciting those models. In order for students to self-assess their models, Lesh, Hoover, Hole, Kelly, and Post (2000, p. 619) posit that those students should be able to judge when their responses need to be improved, or when responses need to be refined or extended for a given purpose, so they can determine when they have finished. The alternative is to continually ask, "Is this good enough?" (known as "satisficing," as coined by Simon, 1957), being the circumstance that they actually do face in professional practice. That also means an encounter with the phenomenon of mathematics-in- biology might not have been entirely satisfying for participants as far as sense making. Carol was not alone in saying:

> For me it was the, the math [in professional development] … 'cause I didn't know I was, I mean, I knew because I know what a dihybrid is, I was supposed to get up, get sixteen possibilities. I knew that. But I didn't know mathematically how to show that, so that's why we just kept doing it randomly, to see if we, what number we ended up with. So the math is what held me up, like, how do they know when to stop?

To summarize, as shown in Table 14.1, two themes emerged from the interviews and observations, the first oriented toward increasing teaching expertise in one discipline by having to address another. That is, since mathematics was neglected in their own secondary education, these participants had had to deal with both the perception and perpetuation of biology as the math-less science, which was not beneficial for preparing their students who had any interest in biology for university study or a career in the field. For some participants this theme played out as a continuation of their efforts to include more mathematics, while for others (e.g., Carol and to some extent Emma) it was recognizing that mathematics needed to be addressed,

Table 14.1 Summary of participants and themes

Theme	Alice	Betty	Carol	Dorothy	Emma
Increasing Biology Teaching Expertise by Use of Another Discipline	Never in doubt, BLOOM materials could not have happened soon enough to please her	Similar to Alice, but willing to sacrifice some students' progress in order to maintain the entire class at about the same level	A repeat implementer, like Alice and Betty; out of a strongly felt duty to her students she at first made charts for herself in order to understand the BLOOM material, and weaning herself from reliance on the Punnett square	Most critical of the BLOOM materials, but also most willing to experiment with them alongside her students, without being entirely sure of the outcome beforehand	Most willing to implement BLOOM materials with fidelity, based on her practice of looking for content that she felt would interest her students
Perception of Emergent Student Self-Efficacy	BLOOM materials contributed, but would have happened anyway	BLOOM materials contributed, but absenteeism prevented optimal progress	Wary at first of her students' abilities to handle BLOOM materials, but progressively convinced by results	Similar to Carol, except that her typically higher level students faltered until they got used to the ambiguity of design challenges having multiple solutions	Similar to Dorothy

and if that meant biting the bullet in order for them to improve as biology teachers, then so be it.

The other theme remained more implicit than the first, perhaps because it was difficult to resolve and thus required some effort to follow. In any event, teachers' uneasiness from having to keep track of students' multiple solutions was assuaged somewhat when students who previously had been on the periphery of class discussions were able to assert their findings with confidence, having discovered their own abilities while the usual leaders in class were faltering without detailed direction. Clearly, exchanging the confusion of one student for that of another is not an end unto itself, but introducing one set of students to improved self-efficacy while another learns to deal with unprecedented yet desirable difficulty (Bjork & Bjork, 2006) needs to be pursued with additional study until those conditions can be replicated consistently.

Discussion and Conclusions

Three of the participant teachers in this study had implemented earlier versions of the BLOOM module, and to describe their first impressions of this implementation as naïve (Moustakas, 1994, pp. 14–16) is probably not as accurate as it would be for the others. In reading about Alice, Betty, and Carol, and what each had to say the reader should keep in mind that these teachers' familiarity with the materials and day-to-day expectations are likely to be grounded in typification (Gubrium & Holstein, 2000, p. 489) already. In fact, none of our participants was a novice in the classroom, with the least experience at 5 years or more, and some cultural and systems reifications of practice (Berger & Luckmann, 1967) may have inured them from, or impelled them toward, testing their own models of inheritance and reforming their own curriculum.

Keeping that in mind, it must be attended to that participants were not averse to introducing socio-mathematical norms for student class negotiation of mathematical expressions (a consideration of importance to professional development suggested by Elliott et al., 2009) and concepts of rarity, which probably would have been foreign to their own mathematical backgrounds. And they did try to embrace this attitude themselves in professional development. Yet, had the BLOOM developers addressed one particular limitation of professional development, then participant effort and effect might have increased substantially: facilitating continuous online contact among participants by providing a shared space for them to post questions, ask for help, and display big ideas they came up with themselves.

What is fairly certain is that the engineering practices (described in NRC, 2012, pp. 41–82 and Appendix F) that informed the BLOOM design challenge and required the student derivation of a mathematical expression in order to detail a solution, remained foreign to even the repeat participant teachers. This was apparent from the participants reflecting as a group at the professional development session after the module implementation had concluded; participant were asked about which aspects of the module they thought were directly related to mathematics and which to engineering. While it was easy for participants to flag the mathematics, their further responses indicated no distinction on their part between their typical classroom procedures and what they took engineering to be at the time the question was asked. In other words, if engineering had occurred during implementation, it was not purposeful engineering of which participants were aware or that they had intended or planned as such.

This should not be surprising when one considers two aspects of the implementation. The first is the NRC's eight categories of engineering practice one of the foundations for developing the BLOOM module:

- Asking questions (for science) and defining problems (for engineering)
- Developing and using models
- Planning and carrying out investigations
- Analyzing and interpreting data
- Using mathematics and computational thinking

- Constructing explanations (for science) and designing solutions (for engineering)
- Engaging in argument from evidence
- Obtaining, evaluating, and communicating information

Given these descriptions alone, it would be expected of participating teachers to read down the list, and check check check each of these items off in turn, because the headings appear familiar, and participants want to head off to the biology and mathematics content anyway. Those are the entries to the module for which their experiences have prepared them, after all, and of course they do all the activities on this list.

Yet it is not until one parses the items, as the NRC does (pp. 41–82) when pitting theoretical explanation versus useful enactment (rather than as the perpendicular axes of Pasteur's quadrant in Stokes, 1997), that what scientists do becomes distinct from what engineers do under each item. While this distinction is handy in promoting a variety of directions for classroom activities under each heading, it is not clear that raising awareness of engineering in apposition to science (thus maintaining the linear hierarchy of the results from primary basic research being transferred to secondary applied research; the analysis dominance over design that prompted all the NSF funded research as previously noted) is the most beneficial for teachers or students.

If Mathematics Was Something Daunting to Be Encountered, What Will Engineering be?

A second aspect of the implementation that might have restricted participant attention to engineering is the relative emphasis on mathematics day in and day out, versus the fewer periods of class time spent on the design challenge, leaving correspondingly fewer opportunities for participating teachers to define an engineering design process for themselves and then refine that with class discussions. There is not only a lot to do for design, but there is a lot to accept about it before doing can occur. For example, Carr et al. (2012, p. 18) provide an apparently comprehensive list of what engineers do (as currently being taught in P-12 curricula), from identifying criteria, constraints, and problems to describing the reasoning to designs and solutions to producing flow charts, system plans, solution designs, blue prints, and production procedures. And every single one is true, but those are activities that experienced engineers do, once they have already encountered and internalized the fundamental property that one enters a design process without any idea about what the problem is, much less what all the solutions might entail. All of that has to be determined, sometimes over and over again until clear enough to make progress. One participating teacher, Carol, displayed substantial anxiety about letting her students leave at the end of a class without a clear resolution, as if she were holding out on her end of a student-teacher contract that guaranteed a singular correct answer to every question she raised.

On the other hand, it did not take much convincing at the BLOOM professional development sessions to get these participating teachers to pose the design challenge as a student driven effort. While not a trivial achievement, this went much more smoothly than the developers anticipated, because there were teachers in previous implementations who were not at all convinced that their students could handle the challenge and thus saw fit to supplement and modify the BLOOM instructional materials at their discretion, thereby reducing the student- driven nature of the materials. In fact, the BLOOM developers were careful to iteratively prototype what Hashweh (2005) refers to as “Teacher Pedagogical Constructions” in order for teachers to have ready-made routines at hand for identifying and discussing naïve concepts with their students.

Finally, there is no dearth of research on either biology teachers learning to teach biology or mathematics teachers learning to teach mathematics, but studies of a teacher in one discipline making sense of what familiar subject matter looks like through the lens of another are somewhat more rare. For that teacher further to touch upon subject matter altogether foreign to P-12, as engineering is for the most part, has seemed up to now out of the question. Yet, standards related to engineering are headed straight for those classrooms, as previously noted, and, for good or ill, it is no longer desirable for biology to offer a refuge for those students who enjoy science without mathematics. That renders the implications of this study (i.e., that biology teachers motivated to improve their understanding and teaching of biology will take the risk of exposing students to novel ways of mapping biology onto other disciplines) of great interest to immediate impending instructional practice.

Key Insights: The Take-Aways

One very important observation to be communicated here is that, during this study, the teachers who entered with anxiety about mathematics and engineering came to terms not only with what they perceived as their personal or historical deficiencies regarding those fields, but also with their apprehensions about incorporating those unfamiliar approaches in their day-to- day instructional methodology. It is no mystery that a large part of this achievement was due to the exposure of all of the participating teachers to one another in the reflective portions of professional development as the implementation was taking place and then afterward. Certainly, those who had more confidence in their own abilities to handle the design challenge displayed and transferred some of that self-efficacy to their colleagues as the implementation ran its course. When other teachers who had been hesitant returned for additional rounds of implementation it was likely due to both previous instructional results and encouragement of the will to persist (itself engendered from friendships that had been struck up) that had produced those results.

Likewise, there were participating teachers who felt at first that the design challenge would prove beyond their students' abilities. Their expectation was that an encounter with the ambiguity of apparently wicked (albeit genuinely well-defined) problems that needed to be deconstructed and attacked without explicit step-by-step direction would inhibit their accustomed low performers into silence. As it turned out, because their otherwise already self-assured high performers needed to collect and regroup in the face of a strangely presented problem, the door was left open for actual collaborative input from those who had shied away from that before.

In closing, one notes that the participants brought a previously reified convention under scrutiny, betraying the haven against mathematics that biology had become at the secondary level. While it is not overreaching to declare this as courageously critical reflection for some of them, it is certainly overdue for them to correct this disservice to secondary level biology students and the sciences in general. That is, providing students with a clearer picture of what professional biologists (and, to some extent, engineers) can do and are expected to do enables them to make better informed choices about their career paths and interests than was possible before.

Appendix A

Protocol for first interview regarding experimental biology unit questions: teachers reflecting on mathematics proposed for inheritance instruction. We realize that experimental content might work for some students and not others. Please tell us the weak points as well as the strong ones.

Category 1: Personal Justification for Increasing Mathematical Exposure/Awareness/Mastery in General Studies, and in Biology Specifically

What math are you comfortable using off the cuff? Is the math you're using for the unit inside or outside your zone of comfort? [prompts: algebra and variables; geometry and progressions]

In your opinion, what place **does** math have in biology instruction? [prompts: on a continuum from good to neutral to bad, say, or with good being an important tool for understanding biological processes and their range and limitations]

In your opinion, what place **should** math have in biology instruction?

You can think of these next questions as ones of did you: learn and then retain the math through reuse; learn and then forget from disuse (certainly my case); or were you never exposed to it?

How was math used to define inheritance concepts when you were:

- A student in secondary school and university
- Learning to teach
- Since you've been at the present school [prompt: depending on who sets policy, well-defined administrative or departmental item?]

The National Research Council says this as part of its framework: **Mathematics serves pragmatic functions as a tool – both a communicative function, as one of the languages of science, and a structural function, which allows for logical deduction. Mathematics enables ideas to be expressed in a precise form and enables the identification of new ideas about the physical world.** Does that support how you feel about introducing math into biology? (2012, p. 64) [National Research Council of the National Academies (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas.* Washington, DC: National Academies Press.]

Does this support what textbooks show or say about use of math in biology?

How did you use math in inheritance instruction before BLOOM? For example, did you use math to explain, calculate, or verify inheritance concepts for yourself before BLOOM?

Was it necessary for you to relate the math you used then to actual biological concepts and processes, or was it sufficient to find a reliable widget for calculation (e.g., a Punnett square) without investigating its limitations as a representation of a biological processes such as independent segregation, independent assortment, gamete formation?

Did you use math on any assessments when teaching inheritance before BLOOM implementation?

Category 2: Reflection on Interaction with Unit Content

When did you need to rely on math during the implementation: can you remember when math was helpful or any times when it was harmful to students' progress or understanding? [prompts: defining combinations; making combinations; counting combinations; predicting combinations, comparing combinations expected theoretically versus observed empirically]

Did you recognize any difficulty that the materials introduced or made worse, that might have gotten in the way of student understanding?

Did you include any items related to math on assessments subsequent to the implementation, and why?

Do you anticipate any circumstances that would cause you to include such items or revise the structure of your exam? [prompts: response to standardized testing of science, administrative or departmental directive]

How do you make sense of the concepts and the sequence of presenting rules in the BLOOM materials? [prompt: inheritance, combinations, expression, design as plan with scientific explanation]

Appendix B

Protocol for second interview regarding experimental biology unit questions: teachers reflecting on math proposed for inheritance instruction. We realize that experimental content might work for some students and not others. Please tell us the weak points as well as the strong ones.

Category 1: Triangulation of Data Analysis

Please look over the section for which your pseudonym is indicated. What do you think is inaccurate?

How would you change that to be accurate?

Category 2: Self-assessment Using the Design Challenge

At what stage of the implementation did you understand what the design challenge was asking students to do? [prompts: professional development, review on my own, while helping students, never really sure]

At what stage of the implementation did you feel confident in answering the design challenge yourself?

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