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Article

Biology Undergraduates' Misconceptions about Genetic Drift

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This study explores biology undergraduates' misconceptions about genetic drift. We use qualitative and quantitative methods to describe students' definitions, identify common misconceptions, and examine differences before and after instruction on genetic drift. We identify and describe five overarching categories that include 16 distinct misconceptions about genetic drift. The accuracy of students' conceptions ranges considerably, from responses indicating only superficial, if any, knowledge of any aspect of evolution to responses indicating knowledge of genetic drift but confusion about the nuances of genetic drift. After instruction, a significantly greater number of responses indicate some knowledge of genetic drift ($p = 0.005$), but 74.6% of responses still contain at least one misconception. We conclude by presenting a framework that organizes how students' conceptions of genetic drift change with instruction. We also articulate three hypotheses regarding undergraduates' conceptions of evolution in general and genetic drift in particular. We propose that: 1) students begin with undeveloped conceptions of evolution that do not recognize different mechanisms of change; 2) students develop more complex, but still inaccurate, conceptual frameworks that reflect experience with vocabulary but still lack deep understanding; and 3) some new misconceptions about genetic drift emerge as students comprehend more about evolution.

INTRODUCTION

Biology educators have articulated the importance of teaching undergraduates the mechanisms of evolution. In a national survey, more than 300 college biology faculty agreed on the importance of evolution instruction in introductory biology sequences, including instruction on evolutionary mechanisms and phylogenetics (Gregory *et al.*, 2011). In fact, evolution was the most agreed upon topic, with 89% of faculty agreeing it was an *essential* topic for biology students to learn. Similarly, in the report BIO2010, the Committee on Undergraduate Biology Education noted that students should understand that "all living things have evolved from a common ancestor through processes that include natural selection and genetic drift acting on heritable genetic variation" (National Research Council, 2003). Evolution is a core concept in biology, and it is also one of the most challenging concepts for students to learn.

Most of the research on students' conceptual difficulties with evolution has focused on natural selection, but understanding random evolutionary processes is also particularly challenging (Garvin-Doxas and Klymkowsky,

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2008; Klymkowsky and Garvin-Doxas, 2008; Mead and Scott, 2010). In the development of the Biology Concept Inventory, "deep-seated, and often unaddressed, misconceptions about random processes" emerged as factors contributing to student difficulties in learning evolutionary and molecular biology (Garvin-Doxas and Klymkowsky, 2008; Klymkowsky and Garvin-Doxas, 2008). This is not surprising, because probability and randomness perplex students of all ages (e.g., Fischbein and Schnarch, 1997; Taleb, 2005; Lecoutre *et al.*, 2006). Students are challenged by both the terminology associated with random evolutionary processes (Mead and Scott, 2010) and the conceptual complexities of these processes (Garvin-Doxas and Klymkowsky, 2008; Klymkowsky and Garvin-Doxas, 2008). Indeed, the most tenacious misconception in biology may be the idea that all processes serve a purpose (Gregory, 2009; Kelemen and Rosset, 2009; Mead and Scott, 2010). This idea is so deep-seated that students fail to even consider random processes as responsible for biological patterns (Garvin-Doxas and Klymkowsky, 2008). The fact that random processes confound students is particularly worrisome, because random processes occur at every level of the biological world, from gene expression (Cai *et al.*, 2006) to clade diversification and extinction (Raup *et al.*, 1973).

Despite these obstacles, understanding random processes such as genetic drift is essential for a deep understanding of the theory of evolution. In contrast to natural selection, genetic drift is nonselective and therefore results in nonadaptive changes in populations (Beatty, 1992). Genetic drift occurs in any finite population and therefore occurs in every population all the time (Futuyma, 2005; Barton *et al.*, 2007). Of particular concern to conservation biologists, drift may overwhelm selection in small populations (Frankham *et al.*, 2002). Drift reduces the amount of genetic variation within populations and tends to increase genetic variation among populations (Frankham *et al.*, 2002; Futuyma, 2005; Barton *et al.*, 2007). Genetic drift is also the theoretical framework for neutral evolution (Barton *et al.*, 2007; Masel, 2012). Thus, biology undergraduates should be able to explain the random process of genetic drift and predict how drift impacts populations (Masel, 2012).

The teaching and learning of genetic drift has been largely overlooked in biology education research. A search in ERIC (performed April 23, 2012) for the term "genetic drift" in the text of any article written over the past 45 yr produced only 13 papers. Most of these papers described methods for teaching genetic drift, but did not report data on how effective those methods are at changing students' conceptions of drift (e.g., Maret and Rissing, 1998; Staub, 2002; Young and Young, 2003). In contrast, numerous studies have focused on undergraduates' scientifically inaccurate conceptions about natural selection (e.g., Bishop and Anderson, 1990; Settlage, 1994; Jensen and Finley, 1996; Anderson *et al.*, 2002; Abraham *et al.*, 2009; Gregory, 2009; Kalinowski *et al.*, 2010; Andrews *et al.*, 2011). An ERIC search for the term "natural selection" produced 317 papers.

In the present study, we used a mixed-methods approach to: 1) describe undergraduates' definitions of genetic drift, 2) identify the most common misconceptions in those definitions, 3) examine differences in students' definitions before and after receiving instruction on genetic drift, and 4) propose a framework for future research that interprets students' misconceptions and illustrates how undergraduates' understanding of genetic drift progresses.

METHODS

Our methodology was mixed. Our qualitative analytical methods aligned with grounded theory and were supplemented with statistical analysis to compare student responses before and after instruction.

In grounded theory, the central question is: "What theory emerges from systematic comparative analysis and is grounded in fieldwork so as to explain what has been and is observed?" (Patton, 2002, p. 133). In practice, grounded theory aims to derive descriptions from the data, as opposed to approaching the data with preliminary explanations. Those data are read and re-read, and from these readings investigators establish categories that explain the data. Once categories are established, investigators review data again and assign units of data, such as quotes from student responses, to categories. Thus, categories serve to organize detailed descriptions of the data. In this way, grounded theory is analogous to inductive science, in which careful and repeated observations enable descriptions. Additionally, grounded theory, like inductive science, may produce hypotheses that can be tested with additional research (i.e., deductive science). Grounded theory was developed by sociologists and is traditionally used to analyze interview data with the goal of developing theories about human actions, interactions, and social processes (Creswell, 2007). In our study, we analyze qualitative data from written responses, focusing on participants' conceptions, rather than the broader context in which the participants are acting.

For this study, we synthesized data collected during two distinct research projects (Table 1). Authors from a National Evolutionary Synthesis Center (NESCent) working group (T.M.A., R.M.P., L.S.M., T.L.M., A.T., and K.E.P.) collected data in preparation for the development of a concept inventory on genetic drift. Authors affiliated with the National Center for Case Study Teaching in Science (C.F.H, D.R.T., and P.P.L.) collected data during a study of the effectiveness of a series of case studies, including one on genetic drift and other evolutionary mechanisms. Combining data sets allowed us to analyze misconceptions about genetic drift from a broad range of students and to capitalize on the different strengths of each project (Table 1). The case study data set allowed us to test for differences between responses collected before and after instruction, whereas the concept inventory data set provided information about misconceptions that occur after more than one exposure to genetic drift instruction, since many of the participants were biology majors enrolled in courses for which introductory biology was a prerequisite. We describe methods used to collect both data sets in the Supplemental Material.

Qualitative Analysis

Our analysis focused on the misconceptions in student responses. Because our community of researchers lacks a consensus on how to characterize knowledge that conflicts with expert ideas, we need to define how we used the term *misconception* in this study (see Gilbert and Watts, 1983; Tanner and Allen, 2005). We defined a misconception as a scientifically

Table 1. The data in this study came from two distinct collaborations

Project	Level of courses	Data	Sample size
Concept inventory	Upper-division biology courses	Interview and written surveys about genetic drift	37
Case study	Introductory biology for majors and nonmajors	Open-ended question before and after instruction about natural selection and genetic drift	319

inaccurate idea about a scientific concept. These inaccuracies may occur before and after instruction. We did not distinguish between ideas generated during data collection and deeply held ideas. We considered the term misconception to be equivalent to the term *alternative conception*, and to be a particular kind of *preconception* or *naïve conception* (Gilbert and Watts, 1983).

In the literature on natural selection misconceptions, the term *misconception* is often defined more narrowly than we have defined it in this study. For example, natural selection misconceptions have been referred to as "deeply rooted" and as "intuitive interpretations of the world" (Cunningham and Wescott, 2009; Gregory, 2009). However, natural selection misconceptions have been explored in depth, leading to more precise definitions of natural selection misconceptions. In contrast, few, if any, studies have focused on students' conceptions of genetic drift. We have used a broad definition of misconceptions that encompasses all students' inaccurate ideas, because considerably more research will be necessary to identify which inaccurate ideas are intuitive, common across diverse populations, and deeply held.

Rigor in qualitative research has been defined as the "attempt to make data and explanatory schemes as public and replicable as possible" (Norman Denzin, as quoted in Anfara *et al.*, 2002, p. 7). Therefore, two authors followed this systematic approach:

1. We (T.M.A. and P.P.L.) independently identified student misconceptions about genetic drift in the concept inventory data set and case study data set, respectively. Thereafter, we combined data sets and completed all analyses in the same place and time, which allowed us to immediately deliberate on any ambiguities.
2. We agreed on an initial list of misconceptions about genetic drift. To create this initial list, we analyzed a subsample of student responses from the combined data set to establish the characteristics of misconceptions.
3. We each coded ~40 responses, identifying the misconceptions in each response to establish that we could reliably classify misconceptions. We discussed any discrepancies until we reached consensus. At this preliminary stage, we identified three general types of student responses: responses that did not address genetic drift, despite explicit instructions to do so; responses containing misconceptions about genetic drift; and responses indicating at least some knowledge of genetic drift. These general types were not mutually exclusive.
4. Using the initial list of misconceptions produced in step 3, we began coding the full data set. Any idea we could not classify after discussion was coded as *undetermined*. Coding the full data set was necessarily iterative. Throughout this process, new misconceptions emerged, our descriptions of existing misconceptions were refined and sometimes subdivided, and the data were recoded accordingly. In all cases, new misconceptions were closely related to misconceptions from our initial list, so it was only necessary to reanalyze responses previously coded as containing a misconception closely related to the newly emerged misconception and responses previously coded as undetermined.
5. After all responses had been analyzed and coded at least once, we re-read all of the responses containing the same misconception, and discussed at length the characteristics delineating each misconception.
6. Toward the end of our analysis, we tested our list of misconceptions to ensure it was exhaustive. We drew a new, random sample of 30 responses from the case study project data set, including questionnaires completed before and after instruction from all six sections, and coded this sample. We found no misconceptions we could not classify with our final coding system. We therefore concluded our list of misconceptions included all but the rarest genetic drift misconceptions held by participating students.

As we analyzed the data, we looked for overarching categories that would enable us to build a framework for future research on students' conceptions about genetic drift. This is the end product of a grounded theory study (Creswell, 2007; Glaser and Strauss, 2010). We designed the framework to facilitate the interpretation of undergraduates' misconceptions about genetic drift and to hypothesize how undergraduates' understanding of drift may progress. To build the framework, three investigators (T.M.A., R.M.P., and P.P.L.) iteratively grouped the full set of misconceptions and named the resulting clusters. We worked to propose a final framework that was derived from the data, not from explanations about student conceptions that we held prior to data analysis. This process continued until all three investigators agreed that the framework was true to the data and suggested testable hypotheses about genetic drift.

Statistical Analyses

We used 319 responses collected as part of the case study project to examine differences in students' conceptions about genetic drift before and after instruction. As described in the Supplemental Material, we used a systematic sampling design to select student responses. We sampled different students' responses before and after instruction, even though this precluded using matched pairs. This approach, which allowed us to include more students, ensured a breadth of responses, even though it limited statistical power by not controlling for individual variation among students. All

Table 2. Frequency of different types of responses observed in full data set (n = 356), in only those responses that addressed drift (n = 244), and before (n = 85) and after (n = 122) introductory instruction

Responses that. . .	% Full data set	% Addressed drift	% Before instruction	% After instruction	p Value[a]
did not address drift	31.5[b]	NA	46.5[c]	23.8[d]	< 0.0001
contained at least one misconception	57.0	83.2	99.0	74.6	< 0.0001
hinted at knowledge of genetic drift, but were too vague to evaluate	7.0	10.2	1.0	17.0	NA
indicated some knowledge of genetic drift	7.9	11.5	1.0	11.0	0.005

[a]p Values indicate significance of Fisher's exact tests comparing counts of responses before and after instruction.

[b]Values in a column may sum to greater than 100%, because a response could indicate knowledge of drift *and* contain a misconception.

[c]The first cell in this column is calculated from all responses collected before instruction (n = 159). The rest of the cells in this column are calculated from the responses that addressed drift (n = 85).

[d]The first cell in this column is calculated from all responses collected before instruction (n = 160). The rest of the cells in this column are calculated from the responses that addressed drift (n = 122).

statistical analyses were conducted in R, an open-source statistical analysis program (R Project for Statistical Computing, 2011).

To assess the hypothesis that instruction improved students' understanding of genetic drift, we tested three predictions generated by this hypothesis. We predicted that before and after instruction the following would be different:

1. Number of students who did not address drift
2. Number of responses that indicated some knowledge of the definition of genetic drift
3. Number of responses containing at least one misconception

We tested these predictions with Fisher's exact tests (Ramsey and Schafer, 2002); for predictions 2 and 3, we excluded responses that did not address drift. The Fisher's exact test is more precise than a chi-squared test when some cells in a contingency table have small sample sizes (Ramsey and Schafer, 2002). A small p value resulting from this test indicates that the counts of responses in the two categories are not independent. In other words, a small p value resulting from the tests described above would suggest that instruction influenced students' responses.

Finally, we used descriptive statistics to examine differences between the frequency of misconceptions before and after instruction in introductory biology courses and among upper-division students. We did not pursue additional statistical analysis for individual misconceptions or categories of misconceptions, as there were small sample sizes for some misconceptions and a lack of independence among groups resulting from responses containing more than one misconception.

RESULTS

Out of 356 student responses analyzed, few defined or attempted to apply the concept of genetic drift without using misconceptions. Even though questions from both data sets specifically asked students to define genetic drift, 31.5% (n = 112) of responses *failed to address drift at all* (Table 2). Among responses that addressed drift (n = 244), only 11.5% (n = 28) indicated some knowledge of the definition of genetic drift. Overall, 83.2% (n = 203) of the responses that addressed drift contained at least one misconception (Table 2). Some responses (n = 25) hinted at knowledge of genetic drift (e.g., included the term *random* or *chance*), but were too vague to be fully evaluated. Note that, because some responses indicated knowledge of genetic drift but also contained misconceptions, the percentages provided here sum to greater than 100%.

Categories of Student Misconceptions Regarding Genetic Drift

In responses that addressed drift (n = 244), we identified five overarching categories of misconceptions: Novice Genetics, Novice Evolution, Associating Genetic Drift with Other Evolutionary Mechanisms, Associating Genetic Drift with Population Boundaries, and Developing Genetic Drift Comprehension. These overarching categories are further divided into 16 distinct misconceptions that we describe below and summarize in Table 3. We also describe the frequency of each misconception (Table 3). We further divide the frequency of each misconception into those collected before and after introductory genetic drift instruction (case study data set) and those collected from students enrolled in upper-division biology courses (concept inventory data set) (Table 3).

Our detailed description of the misconceptions begins with the most novice overarching categories (Novice Genetics and Novice Evolution) and concludes with the most advanced category (Developing Genetic Drift Comprehension). The two categories presented in the middle (Associating Genetic Drift with Other Evolutionary Mechanisms, Associating Genetic Drift with Population Boundaries) do not represent a progression; rather, some responses in each category range from novice to developing comprehension. Within the overarching categories of misconceptions, we have listed misconceptions in decreasing order from highest to lowest percentage of responses that addressed drift **(**Table 3**).** It is important to recognize that although some misconceptions we describe indicated more advanced knowledge than others, responses in the most advanced category still differ in key ways from an expert's conception of genetic drift.

We use quotes from students to illustrate the misconceptions encompassed by each overarching category. In the interest of brevity, we include the most salient sections of a response, rather than complete responses. In some cases, we may have used additional information included in a response

Table 3. Categories of misconceptions, student quotes, and the frequency with which students employed these misconceptions[a]

Misconceptions	Student quotes	% of Total ($n = 244$)	% Before instruction[b] ($n = 85$)	% After instruction[b] ($n = 122$)	% Upper division[c] ($n = 37$)
Novice Genetics *Genetic drift is. . .*		12.7	22.4	9.0	5.4
shared traits or genes.	"Genetic drift [is] when it's the same species but different characteristics." "Genetic drift because both species [have] distinctive commonalities."	7.4	14.1	4.9	0.0
gradual genetic change in a population.	"Genetic drift is where the amount of present alleles change[s] gradually over time." "Genetic drift is a change in genes over time."	4.1	5.9	3.3	5.4
when genes or traits are passed from one individual to another.	"Genetic drift is the passing down of traits while natural selection does not have anything to do with genetics."	1.2	2.4	0.8	0.0
Novice Evolution *Genetic drift is. . .*		20.9	31.8	14.7	13.5
acclimation to the environment that may result from a need to survive.	"It was probably genetic drift. As the butterflies adapted to their new habitat they had to physically change in order for survival." "The evolution of the two butterflies is genetic drift because they developed to their surroundings."	15.6	25.9	11.5	2.7
change resulting from mating between individuals from different species.	"[Genetic drift occurred when] certain butterflies with each gene and characteristics came together in a certain spot and they mated forming new types of butterflies."	4.5	5.9	1.6	10.8
when natural selection cannot or is not occurring.	"[Genetic drift is] the genetic changes that occur when a population is not under selection."	0.8	0.0	1.6	0.0
Associating Genetic Drift with Other Evolutionary Mechanisms *Genetic drift is. . .*		18.8	13.0	13.1	48.6
random mutation.	"[Genetic drift occurs when] due to random mutations, genetic structure can change over time." "The definition of genetic drift is random chance mutation."	7.4	4.7	5.7	18.9
gene flow.	"The movement of genes from one population of a species to another or from one locality to another." "Genetic drift is a chance occurrence that brings genes into a population."	5.7	7.1	4.1	8.1
natural selection.	"Genetic drift occurs to eliminate the less adaptable trait that is not well suitable to the environment."	4.5	1.2	2.5	13.5
any change in allele frequencies.	"[Genetic drift is] the process of changing allele frequencies within a population."	1.2	0.0	0.8	8.1
Associating Genetic Drift with Population Boundaries *Genetic drift is. . .*		32.8	33.0	36.1	21.6
migration with or without acclimation to the environment.	"Genetic drift is when the population moves to a location more suitable to its characteristics." "[Genetic drift occurred] as certain ancestral butterflies moved to different areas, they changed to better suit their new environment."	14.8	16.5	15.6	8.1

Continued

Table 3. Continued

Misconceptions	Student quotes	% of Total ($n = 244$)	% Before instruction[b] ($n = 85$)	% After instruction[b] ($n = 122$)	% Upper division[c] ($n = 37$)
the separation of populations with or without acclimation to the environment.	"[Genetic drift occurs due to] isolation of a population or species by whatever means." "Genetic drift occurs when a sect of a species is separated from the other and changes to adapt to their new environment."	10.2	9.4	10.7	10.8
speciation.	"I believe [it was genetic drift] because I believe at one point both species were one, then separated." "It was genetic drift because some genes changed to create this new species."	7.8	7.1	9.8	2.7
Developing Genetic Drift Comprehension		8.6	0.0	12.3	18.9
Genetic drift is. . .					
a change in genes caused by an isolated event, often a catastrophe.	"Genetic drift involves a natural disaster that dramatically changes the genes in that area."	4.5	0.0	8.2	2.7
limited to small populations.	"Genetic drift is genetics in a smaller populations."	2.5	0.0	3.3	8.1
when an allele is fixed in a population.	"This is when alleles from one population either die out or become the only allele present. It occurs because of random processes. The alleles just happen to die out or become the most prevalent because of chance."	1.6	0.0	0.8	8.1

[a]Frequencies are based on the subset of responses that addressed drift ($n = 244$), not the total number of responses ($n = 356$).
[b]Responses from the case study project.
[c]Responses from the concept inventory project.

to analyze a student's conceptions in order to classify his or her misconceptions. We have lightly edited some quotes for clarity, but have left grammatical and syntax errors when they do not hinder the interpretation of a quote.

Category 1: Novice Genetics. Although a number of definitions for genetic drift exist (Masel, 2012), biologists generally define genetic drift as a change in the allele frequencies within a population resulting from random sampling error from generation to generation (Futuyma, 2005; Barton *et al.*, 2007). Some responses in our sample recognized genetic drift was associated with genetics, but did not recognize it as an evolutionary mechanism. These definitions of genetic drift tended to be vague and brief, indicating only superficial knowledge of genetics.

The most common misconception in Novice Genetics was the idea that genetic drift is, or results in, shared traits or shared genes. In some cases, responses stated or implied that genetic drift causes some differences among individuals, but natural selection causes many differences among individuals:

> "Genetic drift is more likely [than natural selection] because they share many of the same habitats and seem to be similar."

> "Genetic drift equals family members. . .I would have to assume these two butterflies are similar in DNA because of similar shape and habits but not full related because of color and preferred areas to be like meadows and forests."

Some responses in Novice Genetics vaguely described genetic drift as gradual genetic change in a population without describing a mechanism of change:

> "Genetic drift = gradual change in genes."

> "[This is genetic drift because] their similar characteristics indicate that over time the genetics of the species slowly changed."

A few responses in Novice Genetics defined genetic drift as occurring when genes or traits are passed from one individual to another. Responses were not always specific about the units between which traits or genes were passed. Some described genes passing from parent to offspring through reproduction, but others described the transmission of traits between individuals:

> "Genetic drift is when certain desirable characteristics that may occur through mutation are passed on to offspring."

> "Genetic drift is the flow of genes from one individual to another."

Category 2: Novice Evolution. Responses in the Novice Evolution category defined genetic drift as an evolutionary mechanism but conflated the definition of genetic drift with novice conceptions of evolution. The answers indicated little or no knowledge of random occurrences. The most common misconception in Novice Evolution has also been identified and described in studies of students' misconceptions regarding natural selection (e.g., Bishop and Anderson, 1990; Nehm and Reilly, 2007). These responses defined genetic drift as the process, or result, of the environment causing change over time, attributing this change to "adaptation," by which they seemed to mean acclimation to environmental characteristics. Some responses containing this misconception explicitly stated that change resulted from a need to survive:

> "Genetic drift is the most reasonable answer because the sun brings out brightness like the bright butterfly and the shade is dark like the darker butterfly."

> "Genetic drift is genes change over time to fit world changes."

> "Genetic drift [occurred] because the butterflies['] color changed depending on where they spent the most time."

> "Genetic drift is when a species changes due to a specific need to survive or thrive."

Another misconception in Novice Evolution defined genetic drift as an evolutionary mechanism in which change results from mating between individuals from different species:

> "The butterflies were the same color and liked the same environments but began breeding with butterflies of different kinds, possibly because of food scarcity or wind currents."

> "Genetic drift is change due to breeding."

Lastly, a few responses in Novice Evolution contained the misconception that genetic drift is a mechanism of evolutionary change that occurs when natural selection cannot or is not occurring. The descriptions in these responses were so superficial that despite the use of key terms like *natural selection*, the responses failed to indicate any understanding of evolutionary processes. This misconception was not common, but was very clearly articulated in two responses collected from students in different courses in response to different questions:

> "[Genetic drift is] the genetic changes that occur when a population is not under selection."

Category 3: Associating Genetic Drift with Other Evolutionary Mechanisms. Biologists recognize natural and sexual selection, mutation, gene flow, and genetic drift as distinct evolutionary mechanisms. Responses in Associating Genetic Drift with Other Evolutionary Mechanisms confused genetic drift with other evolutionary mechanisms or with evolution in general. The definitions in these responses indicated developing comprehension of evolution, but did not indicate knowledge of genetic drift.

The most common misconception in Associating Genetic Drift with Other Evolutionary Mechanisms defined genetic drift as random mutation. About half of these responses explained that genetic drift results from mutations, while the other half defined genetic drift as the process of mutation or the accumulation of mutations over time. In some cases, students specified a precise mechanism of mutation:

> "Genetic drift = change in a population due to mutation."

> "Genetic drift is the drifting of genes during mutations. A base pair is usually cutoff, that alters the gene sequence leading to changed genes."

Another misconception in this category defined genetic drift as gene flow. Specifically, these responses described genetic drift as the process of alleles entering or leaving populations or as the process of alleles from different populations "mixing." Some responses described the movement of genes, rather than the movement of alleles. Notably, Nehm and Reilly (2007) identified this misconception in undergraduates' responses to an open-response item designed to measure knowledge of natural selection:

> "Genetic drift involves the movement of alleles out of populations/gene pools to new environments."

> "Gene exchange between different populations of animals. Results in an increase or decrease of a specific type of gene."

The third misconception in Associating Genetic Drift with Other Evolutionary Mechanisms defined genetic drift as natural selection. In some cases, these definitions of natural selection were nuanced and accurate; in other cases, responses were less detailed, but implied or described an interaction between traits and the environment resulting in differential reproductive success, survival, or fitness. One response defined genetic drift as sexual selection:

> "Genetic drift occurs because survival of the fittest so if some alleles that are passed down to offspring provide a benefit, those alleles are more likely to get passed on to their offspring."

> "Genetic drift is the gradual change in the frequency of specific alleles in a population to be more or less common [and]. . .occurs when there is a change in the environment that makes specific traits more or less favorable for fitness."

Finally, a few responses in this category defined genetic drift as any change in allele frequencies:

> "Genetic drift is when there is a change in the allele frequency of a population." "Drift is the alteration of genes by anything, including chance."

Category 4: Associating Genetic Drift with Boundaries between Populations. Biologists recognize the founder effect to be one scenario in which genetic drift can occur. Essentially, when a small random sample of individuals from a larger population become the founders of a new population, they are likely to carry only a fraction of the genetic variation of the original population (Futuyma, 2005). Additionally, founding populations are often small and are therefore likely to be further impacted by genetic drift for many generations following the founding event. Moreover, genetic drift and natural selection can lead to reproductive isolation in a peripheral population, such as a founding population. This process is called peripatric speciation (Futuyma, 2005). No responses in Associating genetic drift with boundaries between populations came close to indicating knowledge of the nuanced concepts just described. However, these responses defined genetic drift as movement, separation, and/or speciation, which hinted at knowledge of, or at least exposure to, founder effect as an example of genetic drift.

The most common misconception in Associating Genetic Drift with Population Boundaries defined genetic drift as migration, by which responses typically seemed to mean emigration. In the interest of preserving student ideas, we have also used the term *migration* to describe emigration or immigration. In some cases, responses described migration followed by adaptation to the environment. The descriptions of adaptation in these responses were similar to those in Novice Evolution in that they described adaptation as acclimation to environmental characteristics, but these responses were distinct in that they also discussed the movement of individuals. The units discussed in these responses included individuals, species, and populations. Some responses discussed individuals or groups moving to locations better suited to their traits.

The terms *migration* and *gene flow* are often used interchangeably by experts, who recognize that migration is an evolutionary process only when it leads to a change in allele frequencies. There was no indication that students understood this subtlety. The responses in this category differed from those that defined genetic drift as gene flow, because they did not mention the movement of alleles or genes:

> "Genetic drift is when a certain species migrates to another location."

> "Genetic drift would be where members of a population with different traits move to an environment that fits those traits."

> "Genetic drift would take place if the butterflies would have migrated to another climate and adapted to their surroundings by the means of migrations."

A similar misconception defined genetic drift as the separation or isolation of populations. In some cases, responses discussed separation followed by adaptation, by which they seemed to mean acclimation, to a new environment:

> "Genetic drift generally happens when part of a species population is separated and become[s] distinguished and change[s]."

> "Genetic drift is when members of the same species get separated by environmental forces and over time develop differently."

The third misconception in this category defined genetic drift as speciation. While it is possible for genetic drift to contribute to speciation, these responses did not provide an explanation for how speciation would occur. About half of these responses defined genetic drift as speciation following the separation of populations:

> "These species of butterflies were once the same then slowly over time began shifting into one species that prefer sunny meadows and another that prefers dense woodlands."

> "Genetic drift occurs when an offshoot of a population starts to develop traits that separate it from the original population, usually by a chance act."

> "Genetic drift happens when two species become isolated from each other or no longer reproduce, creating a cross breeds."

Category 5: Developing Genetic Drift Comprehension. Biologists recognize many nuances of the process of genetic drift. For example, genetic drift can result from random sampling of gametes during sexual reproduction, as well as random sampling of individuals, and their gametes, resulting from a population bottleneck (Futuyma, 2005). Experts recognize drift occurs in all finite populations, but is likely to have a more pronounced impact given a small effective population size (Barton *et al.*, 2007). Experts also know genetic drift *can*, but does not always, lead to the fixation of alleles, and that genetic drift tends to decrease genetic variation within a population and increase variation among populations (Frankham *et al.*, 2002).

Responses in Developing Genetic Drift Comprehension indicated some knowledge of genetic drift. However, the definitions in this category placed inaccurate limitations on the circumstances under which genetic drift can occur.

The most common misconception in Developing Genetic Drift Comprehension defined genetic drift as, or as resulting from, an isolated event, often a catastrophe. These responses did not recognize genetic drift as a process occurring each generation:

> "Genetic drift is where there is some event that decreases the variation in a population."

Another misconception in Developing Genetic Drift Comprehension limited genetic drift to small populations:

> "Genetic drift is a change in allele frequency due to a random genetic occurrence in a small population."

The least common response in Developing Genetic Drift Comprehension described genetic drift as allele fixation, rather than describing fixation as a potential result of genetic drift:

> "[Genetic drift is] when an allele gets fixed on a population."

> "[Genetic drift is] allele fixation due to limited gene pool."

> "[Genetic drift is when] a random event knocks out one genotype."

Vague Responses That Hinted at Knowledge of Genetic Drift

Responses that hinted at knowledge of genetic drift used terms such as *random* or *chance* but otherwise did not indicate knowledge of genetic drift. In some cases, the term *random* or *chance* was embedded in misconceptions, but in most cases these responses were simply too vague to evaluate:

> "Genetic drift is all about chances to the outcome of the offspring."

Responses Indicating Some Knowledge of Genetic Drift

Responses indicating some knowledge of drift ranged considerably in quality. Some responses provided precise and nuanced definitions of genetic drift, others gave brief but accurate descriptions of drift, and some responses included misconceptions.

The following quote was one of the most articulate responses in our sample. In particular, the subtle and precise language differentiates this response from responses containing misconceptions. Though the response discusses an event or catastrophe leading to genetic drift—like responses in Developing Genetic Drift Comprehension—the use of the introductory clause "for instance" suggests that the student recognizes this is one example of drift, rather than the only circumstance under which drift takes place:

> "Genetic drift is evolution that occurs purely by chance. For instance, an F_1 generation could have 10 red flowers, 10 pink flowers, and 10 white flowers. If all the white flowers are accidentally killed or something happens, their genes will not be passed on to future generations."

In contrast, the next quote demonstrates how a response can indicate some knowledge of genetic drift and contain a misconception. The first sentence of the response confuses genetic drift with selection, while the second sentence indicates knowledge of genetic drift:

> "[Genetic drift occurs when] through sexual or natural selection, certain alleles are favored. Additionally, it may just so happen that an allele becomes more or less prevalent though it neither helps nor harms individuals within a population."

Results of Statistical Analyses

We used statistical analyses to address three predictions about student learning. We tested these predictions using data from the case study project ($n = 319$), because this project collected data before and after introductory-level genetic drift instruction. We predicted that 1) the number of students who did not address drift, 2) the number of responses that indicated some knowledge of the definition of genetic drift, and 3) the number of responses containing at least one misconception would all be different before and after instruction.

All three of the predictions about student learning were supported by our data (Table 2). In all cases, students exhibited more knowledge of genetic drift after instruction. The number of responses that did not address drift was significantly different before and after instruction (Fisher's test, $p < 0.0001$; Table 2), suggesting that students in these courses did not address drift before instruction because they had little or no knowledge of the concept. To test our second and third predictions, we examined only the responses from the case study data set in which students addressed drift ($n = 207$). The number of responses indicating some knowledge of genetic drift was different before and after instruction ($p = 0.005$; Table 2). Additionally, the number of responses containing at least one misconception was different before and after instruction ($p < 0.0001$; Table 2).

When we examined the frequency of student responses containing each of the 16 distinct misconceptions at different stages of instruction, we noticed that while some misconceptions were less common among students who had received genetic drift instruction, other misconceptions were *more* common following instruction (Table 3). Specifically, the misconceptions in Novice Genetics and Novice Evolution were less common after introductory instruction and among upper-division students, whereas misconceptions in Developing Genetic Drift Comprehension were absent before instruction, but increasingly common with more instruction (Table 3). The frequency of misconceptions in Associating Genetic Drift with Other Evolutionary Mechanisms and Associating Genetic Drift with Population Boundaries remained about the same before and after introductory instruction, but among upper-division students these two categories diverged (Table 3). Misconceptions in Associating Genetic Drift with Other Evolutionary Mechanisms were substantially more common among upper-division students than among introductory students, whereas misconceptions in Associating Genetic Drift with Population Boundaries were less common among upper-division students than among introductory students (Table 3).

DISCUSSION

Our observations represent the first effort, to our knowledge, to describe students' conceptions of genetic drift and how those conceptions change over time. Among students who addressed genetic drift in their responses, nearly all (99%) undergraduates in introductory biology courses had misconceptions about genetic drift before instruction, and almost 75% retained misconceptions after explicit genetic drift instruction (Table 2). Furthermore, undergraduates who had completed introductory biology and were enrolled in upper-division biology courses for biology majors still had serious misconceptions about genetic drift (Table 3).

To facilitate future research on student conceptions of genetic drift, we propose a framework to interpret students' conceptions about genetic drift and to describe how those conceptions change as students learn. This framework suggests three hypotheses regarding undergraduates' conceptions of genetic drift. The rest of this paper presents the framework and hypotheses, followed by implications for instruction and future research.

Framework

Our framework includes the five broad categories of misconceptions identified during our qualitative analysis. The arrows between categories of misconceptions in our framework represent ways in which students' conceptions may be changing as they learn (Figure 1). At one end of the framework are two categories of misconceptions most common among students before genetic drift instruction (Novice Genetics and Novice Evolution). Responses including misconceptions in these categories indicated no knowledge of genetic drift and only superficial—if any—knowledge of evolution. In the middle of the framework are two categories of misconceptions (Associating Genetic Drift with Population Boundaries and Associating Genetic Drift with Other Evolutionary Mechanisms) that were more common in students' responses after some genetic drift instruction. These responses tended to use appropriate terminology about evolution, but did so in a way that revealed misconceptions and was often imprecise and disorganized. At the other end of the framework is the category of misconceptions indicating some knowledge of genetic drift, but also some confusion (Developing Genetic Drift Comprehension). Misconceptions in this category were most common among upper-division students who presumably had the most exposure to genetic drift.

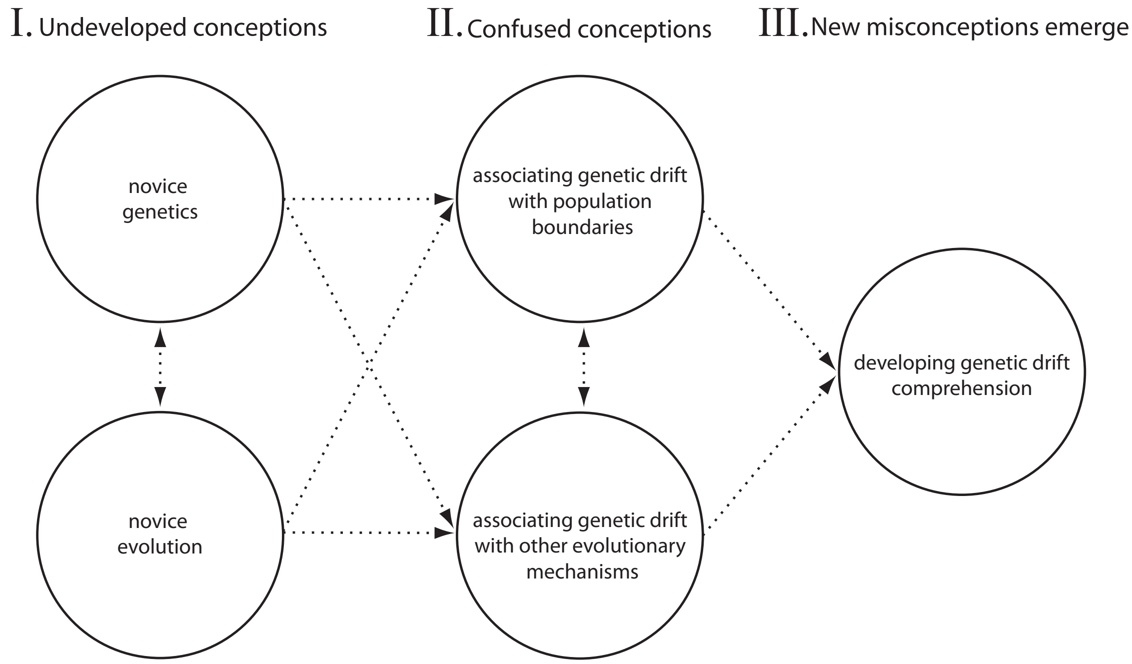

Figure 1. This framework hypothesizes how students' conceptions of genetic drift change over time. Each circle represents an overarching category of misconceptions. Arrows represent the ways in which students' conceptions may be changing as they learn. (I) Students enter introductory biology with undeveloped conceptions of evolution that do not distinguish among mechanisms of evolutionary change. (II) Students' conceptual frameworks of evolution grow more complex, but are still highly inaccurate. (III) Students reject some misconceptions but form new ones regarding inaccurate constraints on when drift occurs.

We did not include a stage representing Expertise in Genetic Drift in our framework, because we derived our framework solely from our data. The standard for expertise would be for students to comprehend genetic drift without misconceptions and to correctly apply their comprehension to novel problems dealing with drift. Students in our data set did not demonstrate this level of expertise. For example, we asked the participants in the concept inventory study to explain experimental results using their knowledge of genetic drift and none were able to do so.

On the basis of framework, we propose three hypotheses regarding undergraduates' conceptions of genetic drift. First, we hypothesize that most students enter introductory biology courses with an undeveloped conception of evolution that does not distinguish among mechanisms of evolutionary change (Figure 1, I). Common misconceptions documented in studies of students' conceptions of natural selection were actually common misconceptions about genetic drift as well (Bishop and Anderson, 1990; Nehm and Reilly, 2007; Gregory, 2009). For example, students defined genetic drift as acclimation to the environment. The fact that these common misconceptions are associated with drift, as well as natural selection, suggests they are actually misconceptions about evolution in general. It appears that students who know nothing about genetic drift are using the context of the question or cues in class to associate genetic drift with evolution. They are then defining genetic drift as they would define evolution or natural selection, perhaps because they think all evolution is natural selection (Jakobi, 2010). If misconceptions in Novice Evolution do in fact become less common after instruction, as our data suggest (Table 3), that would support the hypothesis that students begin with a simplistic conception of evolution that grows more complex as they learn.

Second, we hypothesize that students' conceptual frameworks of evolution grow more complex as they learn, but the added complexity is not necessarily more accurate than their previous, less complex, conceptual frameworks, nor is it expertly organized (Figure 1, II). Students seem to be gaining knowledge of biology vocabulary and concepts, but still lack deep understanding of concepts and scientifically accurate connections among concepts. Their definitions of genetic drift mix misconceptions, imprecise terminology, and irrelevant information with some accurate information. Responses containing misconceptions in the two categories at the center of our framework illustrate this confusion (Figure 1).

Student conceptions probably do not skip from the novice to the developing comprehension end of our framework, but instead must move through the muddled intermediate stage (Figure 1). The challenge for us as instructors is to move students through this stage effectively and efficiently, especially in introductory courses. An exciting area of future research will be to test the efficacy of teaching modules geared to addressing this issue.

Third, we hypothesize that genetic drift instruction leads to the rejection of some misconceptions and the formation of new ones (e.g., Yip, 1998). We observed that after instruction, fewer students had misconceptions in Novice Genetics and Novice Evolution, but more students had misconceptions in Developing Genetic Drift Comprehension (Figure 1, III). Among upper-division students, 48.6% had misconceptions in Associating Genetic Drift with Other Evolutionary

Mechanisms. This is a substantially larger percentage than we observed among introductory students before (13.0%) or after (13.1%) instruction, suggesting additional genetic drift instruction revealed or generated misconceptions in this category. This result is simultaneously encouraging and discouraging. It is encouraging, because it indicates students' ideas are changing. But it is discouraging in that most students still had misconceptions as upper-division biology undergraduates. It remains to be seen, through additional research, what conditions contribute to the development of Expertise in Genetic Drift (i.e., understanding and application without misconceptions).

Implications for Instruction

Our observations suggest that genetic drift is a challenging topic for students to learn. We have not found any exercises to teach genetic drift that have been assessed for impact on student learning, but a number of scholars have proposed ideas for teaching genetic drift and improving an instructor's degree of comfort with the concept (e.g., Staub, 2002; Young and Young, 2003; Masel, 2011 [includes a description of the classic experiment by Peter Buri], 2012).

Though it remains unclear what strategies might effectively facilitate student learning of genetic drift, our observations indicate one potential problem to avoid. Instruction that provides limited examples of genetic drift in action may inadvertently teach students that drift occurs *only* in such cases. For example, if instruction focuses on the founder effect, students may extrapolate that genetic drift only occurs when individuals move from one location to another or when a subset of a population is isolated from the larger population. Alternatively, students may assume genetic drift only occurs in small populations when scenarios used in class focus exclusively on drift within small populations.

Implications for Future Research

Evidence is accumulating that the student misconception that *need is a rationale for change* is common across biology concepts. Though biological explanations including the term "need" are not necessarily illegitimate (Zohar and Ginossar, 1998), teleological reasoning commonly results in misconceptions. The most common misconception we observed among students was defining genetic drift as acclimation to the environment and, in many cases, describing acclimation as resulting from a need to survive. The most common misconception about natural selection is also the idea that individuals or populations change because they need to (Gregory, 2009). This misconception extends beyond conceptions of evolution as well. When asked to explain pictures of biological phenomena, such as a plant growing toward the sun or a group of birds flying in a V formation, the most common idea provided by elementary and secondary school students was that organisms changed because they needed to (Southerland *et al.*, 2001). Adults who had taken multiple college-level science courses also commonly explained natural phenomena as existing to fulfill a need (Kelemen and Rosset, 2009). If this single (albeit tenacious) misconception is affecting students' ability to learn concepts throughout biology, instruction specifically designed to help students think critically about this sort of reasoning could have an impressive impact on student learning. Future research can explicitly focus on determining the pervasiveness of the idea that need is a rationale for change in biological systems and on effective strategies for changing this misconception to a scientifically accurate explanation.

Future research is also necessary to fill out and refine our framework of how students learn genetic drift. Interviews will be valuable to gain deeper insight about student conceptions and how they change with instruction. A broader student population would also be valuable. For example, studying a larger sample of advanced undergraduates will be necessary to understand how student conceptions of genetic drift progress, including how instruction reveals or creates new misconceptions. Furthermore, different questions are likely to elucidate additional misconceptions (Nehm and Ha, 2011).

Finally, future research can document how experts define genetic drift, as well as outlining the key concepts and skills needed to demonstrate expertise in genetic drift. Genetic drift is fundamental to evolution, yet often overlooked. For example, *Teaching about Evolution and the Nature of Science* (National Academy of Sciences Working Group on Teaching Evolution, 1998) outlines the major themes in evolution (Ch. 2) but never mentions genetic drift. In the more recent *Vision and Change* (American Association for the Advancement of Science, 2011), evolution is included in the list of core concepts that all undergraduates should understand but genetic drift is hardly mentioned. To correct this oversight, genetic drift experts and biology education experts need to collaborate to describe what a student who has a complete understanding of genetic drift should be able to do with that knowledge. It would also be useful for experts to think about the necessary scaffolds for learning genetic drift, as well as the recommended timing of scaffolding, for example, in high school biology, undergraduate introductory biology, and undergraduate advanced biology. We have begun to address this aim by uncovering misconceptions about genetic drift among biology undergraduates, and future research on student conceptions of drift has the potential to be just as fruitful.

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