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Genetics Education

Innovations in Teaching and Learning Genetics

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Essay Contest Reveals Misconceptions of High School Students in Genetics Content

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ABSTRACT

National educational organizations have called upon scientists to become involved in K–12 education reform. From sporadic interaction with students to more sustained partnerships with teachers, the engagement of scientists takes many forms. In this case, scientists from the American Society of Human Genetics (ASHG), the Genetics Society of America (GSA), and the National Society of Genetic Counselors (NSGC) have partnered to organize an essay contest for high school students as part of the activities surrounding National DNA Day. We describe a systematic analysis of 500 of 2443 total essays submitted in response to this contest over 2 years. Our analysis reveals the nature of student misconceptions in genetics, the possible sources of these misconceptions, and potential ways to galvanize genetics education.

THE rapid advances in genetic research, the popularity of the topic in the news and in current popular television shows (*e.g.*, CSI: Crime Scene Investigation), and the direct role that genetics plays in human health and reproduction make it a scientific discipline that everyone needs to understand. Yet, several studies reveal that students fail to critically understand the genetics knowledge taught in the classroom, and this lack of understanding translates to an inability to apply basic knowledge to their everyday lives (Lewis and Wood-Robinson 2000; Lewis and Kattmann 2004).

State science standards reflect the important role that genetic advances are playing in our lives. More than 80% of middle and high school science standards adopted since 2003 include terminology on the Human Genome Project, bioethics, cloning, stem cells, and/or other biotechnology terminology that did not exist in previous versions of the standards. However, even the adoption of national science standards, which include the coverage of genetics concepts, does not guarantee understanding of the concepts. The compulsory science education standards in England and Wales, for example, failed to yield deep conceptual understanding in genetics for their students (Lewis and Wood-Robinson 2000). The important role genetics plays in society, human health, and our responses to the environment makes these deficiencies in genetics content knowledge revealed by state, national, and international standardized tests even more troubling. Therefore, a strategic effort to improve secondary genetics education is especially needed.

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MISCONCEPTIONS AND CRITICAL THINKING

One strategy that can have an impact on student understanding of a specific discipline is to encourage deep, critical thinking about that discipline. In an age where at least superficial information is at our fingertips on a limitless number of topics including genetics, we must find methods of ensuring an enduring understanding of this information. Because students often learn only passively through lectures, reading assignments, or cursory searching of the Internet, developing critical thinking skills is necessary to ensure a level of literacy and the eventual ability to apply the knowledge (Connally and Vilardi 1989; Rivard 1994; Keys 1999). Providing students with an opportunity to explore challenging areas in genetics through writing is one manner of achieving this goal.

Research on student learning suggests that student misconceptions serve as barriers to student achieve-

TABLE 1

NAEP test results in 2000 for science reveal a deficit in student understanding of core genetics concepts (O'Sullivan *et al.* 2003)

Theme	Grade	Students with complete/essential answers (%)	Students with partial answer (%)	Students with unsatisfactory answer (%)
Classification	8	23	16	58
Theory of evolution	8	53	NA	45
Reproduction	12	61	NA	39
Evolutionary relationships	12	25	NA	70
Darwin's theory of evolution	12	51	NA	47
Genes[a]	12	21	45	30
Mutation[a]	12	2	33	58
Interpreting genetic material[a]	12	1	1	83
Genetic disease[a]	12	5	31	56
Recombinant DNA usage[a]	12	8	27	58

Percentages may not total to 100 due to rounding and student omission (*i.e.*, no answer was given).
[a] These questions are in the molecular and human genetics category.

ment. These misconceptions are often based on personal experiences and are difficult to bypass en route to meaningful understanding in any content area (Gelman and Gallistel 1986; Wellman 1990). Even after instruction designed to address scientific content in an area where misconceptions are held, many students do not reconstruct their thinking. Only those students able to deconstruct their knowledge and reconstruct it using critical thinking and logical reasoning appear to have fewer misconceptions even after high-quality instruction (Lawson and Thompson 1988). Similarly, conceptual change generally occurs only if a learning experience can demonstrate both that a student's explanation is insufficient and that an alternative explanation is more applicable (Posner *et al.* 1982).

The National Assessment of Education Progress (NAEP) assesses proficiency of U.S. students in a variety of content areas, including science, using a random sampling of students from the 4th, 8th, and 12th grades. The last NAEP tests in science were administered in 1996, 2000, and 2005. Unfortunately, the data from the 2005 test is still not completely accessible to the public. However, an analysis of the 2000 NAEP test results reveals dramatic deficiencies in genetics content knowledge at both 8th and 12th grades. Mastery of 12 concepts from earth, physical, and life sciences is required for students to demonstrate proficient or advanced knowledge in the sciences; one-quarter of these concepts are in the field of genetics (O'Sullivan *et al.* 2003). The NAEP test results reveal specific deficits in student understanding of classification, evolution, mutation, and DNA technology as shown in Table 1. Publicly available data on the 2000 NAEP science assessment (at http://nces.ed.gov/) provides sample questions and answers from students, as well as the criteria for scoring answers as "complete or essential, partial, or unsatisfactory." We specifically examined the subset of data regarding the broad category of molecular and human genetics (footnote *a* in Table 1).

All questions referring to genes, mutation, cell differentiation, genetic disease, and recombinant DNA usage for 12th grade students had a difficulty of "hard" and required a written response. This type of question enables investigators to explore student thinking in more depth. The example for the year 2000 provided an adapted text that was taken from an article in the March 1990 issue of Discover magazine. This article was based on the work of Richard Mulligan and other geneticists that are currently examining the use of viruses as vehicles for introducing genes into human cells as a form of therapy for genetic diseases in humans. A majority of students were not able to describe a gene, its structure, or its function. It was very rare for students to have a thorough understanding of the types of mutations that occur, the causes of those mutations, and the physiological effect of gene alterations. Moreover, few were able to transfer the knowledge from the article to the information they had learned in class about inherited diseases.

Therefore, to encourage a transformation from passive knowledge in genetics gained via classroom lectures, the National DNA Day Essay Contest (http://www.genednet.org/pages/k12_dnaday08.shtml) was established by K. R. Mills Shaw, Director of Education at the American Society of Human Genetics (ASHG), to provide a distinct opportunity for students to think critically and articulate scientific arguments related to genetics. Teachers from across the country were invited to participate through list serves, blast e-mails, and the ASHG education website, http://www.genednet.org. Each year two questions have been provided: one to allow students to explore the methods and research that genetics entails and the second to explore the ethical, legal, and social issues influenced by genetics (see Table 2).

TABLE 2

Essay contest questions in 2006 and 2007

Year	Question
2006	Why is it important for everyone to know about genetics?
2006 and 2007	If you could be a human genetics researcher, what would you study and why?
2007	In what ways will knowledge of genetics and genomics make changes to health and health care in the United States possible?

Table 3 summarizes the number of essays submitted during each year of the contest. The students who wrote the top three essays for each question were declared first, second, and third place winners through the judging process described in METHODS. These students were awarded $350, $250, and $150, respectively. The monetary awards were made possible by the sponsorship of Applied Biosystems (Foster City, CA). While many essays demonstrated a clear understanding of genetics and its implications, a significant number of contributed essays revealed firmly held misinformation and misconceptions by U.S. students in grades 9–12. This article examines those misconceptions, provides possible explanations for their origins, and suggests ways that scientists, professors, and teachers can collaborate to improve genetics education at the K–12 level.

METHODS

Judging of essays: All aspects of the National DNA Day Essay Contest were managed online from initial advertisement to final judging. Information technology specialists from ASHG and the Genetics Society of America (GSA) were able to adapt existing society resources to facilitate essay acceptance, cataloging, and scoring. Judges were recruited from the active membership of ASHG, GSA, and the National Society of Genetics Counselors (NSGC). Three groups of judges were utilized. Each year students were given a choice between two essay questions. The questions from 2006 and 2007 are highlighted in Table 2. The first group of judges read large groups of essays on either of the two essay topics, scanning these essays to ensure they fulfilled all criteria and addressed all aspects of the judging criteria. The criteria were slightly different for each of the two questions and were all published online for all students and teachers. The scoring criteria for the 2007 questions are documented in Table 4. Essays not fulfilling these criteria after being reviewed by at least two judges were removed from more detailed consideration. The second group of judges scored ~10–15 essays in depth, providing a score (from 1 to 10) in each of the five categories. Each essay was scored by at least three independent judges. Scores were tabulated and the 10 essays with the highest scores for each topic were named as finalists. The last set of judges reviewed and scored each of the finalist essays with the highest-scoring essays being chosen as winners. One hundred ten members of the ASHG, GSA, or NSGC membership served as judges each year. The entire adjudication process is reviewed in Figure 1. This system allowed us to perform all judging anonymously and ensure that each essay was read and scored by multiple independent reviewers while simultaneously investigating each essay for scientific accuracy.

Identification of misconceptions: All judges, along with scientists on ASHG staff, were asked to examine each essay for misconceptions or incorrect statements and forward this information along with their scores. All misconceptions were collected over 2 years from individual judges but were placed into categories by two individual coders (K. R. Mills Shaw and K. Van Horne) on the basis of the genetic topic that the misconception addressed (Table 5). These topics were generated *de novo* after reviewing all the misconceptions submitted from judges and after K. R. Mills Shaw and K. Van Horne additionally independently evaluated 125 randomly selected essays from each year (2006 and 2007). All misconceptions were then cataloged under these specific topic areas to better characterize the areas where misconceptions are most common (seen in Table 6). Five hundred essays, or 20%, were randomly selected for this level of systematic review. Specifically, every fourth essay was analyzed in detail. If, however, essays were deemed completely unsatisfactory for review (*e.g.*, too short, too poorly defined, too poorly written), the essay was not included in the systematically reviewed sample of 500. A misconception/misunderstanding was identified as any clearly written statement that did not accurately reflect the nature of genetic science, technology, or research as defined by K. R. Mills Shaw and J. A. Boughman, both Ph.D. scientists with a background in genetics. Essays where language or communication barriers were obvious (due to vocabulary, grammatical,

TABLE 3

Essay contest participation in 2006 and 2007

	2006	2007
Total number of essays received	1519	927
Number of states represented	27	42
Number of teachers represented	165	387

TABLE 4

Essay contest scoring guidelines for 2007

Question	Topic to be included	Points possible
If you could be a human genetics researcher, what would you study and why?	Development/statement of hypothesis	10
	Discussion of current knowledge in field	10
	Discussion of importance of research topic	10
	Discussion of experimental design	10
	Presentation (spelling and grammar)	10
In what ways will knowledge of genetics and genomics make changes to health and health care in the United States possible?	Discussion of the knowledge we are gaining in genomics	10
	Discussion of the current state of health care	10
	Discussion of potential changes at a personal level	10
	Discussion of potential changes at a broader level	10
	Presentation (spelling and grammar)	10

and spelling errors) were not included as part of this review. Once misconceptions were identified, coders both independently and in communication with each other cataloged misconceptions according to topic to ensure consistency in grouping. The quantitation of the examples revealed in this article reflects observations from analysis of the critical writing from 500 high school essays (9th–12th grade submissions).

RESULTS

Essays collected represent data from multiple states, grades, and classroom teachers: All essays were submitted online. In the online submission form we collected demographic data on all students and their teachers, including their grade, city, state, and school. In both years of the contest we included a rule that stated only three essays per teacher for each question, for a total of six essays per teacher, would be accepted. However, this rule was often overlooked, and teachers would submit essays from their entire classrooms. Thus, while we collected more essays in 2006, this total number of essays reflects a representation of fewer classrooms. In 2007 we rectified this problem by adding an algorithm that blocked any more than three essays from the same teacher. The data presented in Table 3 show that the essay contest grew between years 1 and 2 in the overall number of classrooms reached and that the essays collected represent a wide geographical distribution. In 2007, we did not receive essays from Alaska, Hawaii, Vermont, South Dakota, Wyoming, Maine, Washington, DC, Nebraska, or Mississippi despite sending out multiple e-mail solicitations to teacher contacts in those states.

Identification of misconceptions and misinformation from student essays: During the process of reading and scoring essays, judges were asked to identify and document examples of misconceptions in their essays. Additionally, all essays were cursorily scanned by either K. R. Mills Shaw or K. Van Horne. Tables 5 and 6 provide an overview of the topics where misconceptions are common as well sample statements taken directly from student essays. While several hundred individual misconceptions were identified during the course of judging and review, many of the individual misconcep-

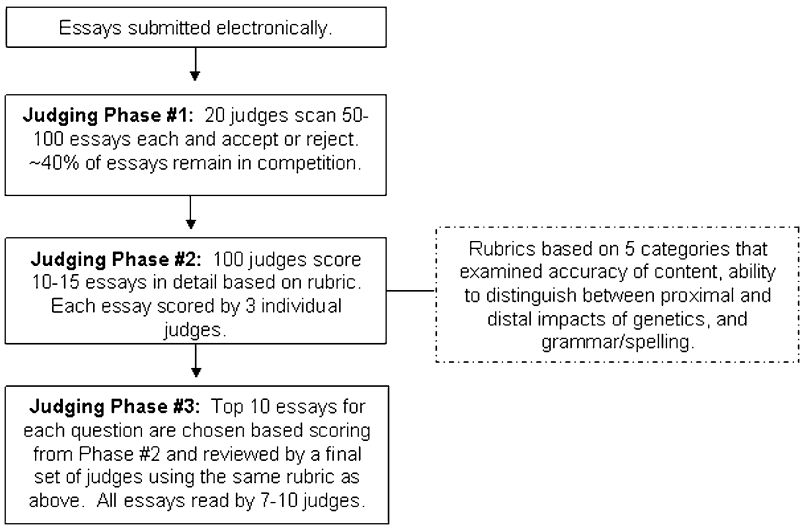

FIGURE 1.—Schematic of process involved in selecting finalist essays.

TABLE 5

Key ideas/subtopics used to categorize misconceptions

Topic	Key ideas/subtopics
Genetic technology	Realistic *vs.* nonrealistic uses
	"Genohype"
	Role of gene therapy in *curing* genetic disease
Deterministic nature of genes	Genes determine all traits
	One gene, one trait
	Lack of environmental influence
	Lack of multigene involvement in traits
Patterns of inheritance	Probability
	Types of inheritance
	Misunderstanding modes of inheritance
	Interpretation of data from Punnett squares
	Understanding the origin of chromosomal anomalies (monosomies, trisomies)
Nature of genes and genetic materials	Role of different nucleic acids in genetics
	Central dogma
	Description of a gene
	Chromosomes and genes
	DNA and living organisms
Genetic basis of disease	Multigene involvement in disease
	Environmental influence in disease
	Difference between genetic and inherited disease
	Difference between viral, sexually transmitted, and genetic diseases
Genetics research	Process of research
	Time frame of research
	Topics of research
Reproductive technology	Eugenics
	Cloning
	Preimplantation genetic diagnosis

tions could be categorized under broad topics in genetics (summarized in Table 5). To quantify the frequency of these common misconceptions we reanalyzed 500 (~20%) of the essays, which included 250 essays chosen at random from each year's submissions. Individual misconceptions were identified and cataloged. After cataloging each misconception in the 500 essays and defining the categories of genetics in which they fell, "common" categories were defined by those being present in at least 5% of the essays examined. Of the 500 systematically reviewed essays, 278 (55.6%) revealed at least one obvious misconception. Another 101 essays (20.2%) were recognized for having two or more misconceptions. Misconceptions that were linked to essays with obvious language or writing barriers were excluded from quantitative analysis to avoid overrepresentation in our quantitative analysis. The prevalence of misconceptions per topic area is summarized in Figure 2.

Standards and common areas of misconceptions: Misconceptions were identified and categorized into a general topic area. We then examined how standards were related to these main topic areas, specifically patterns of inheritance and the deterministic nature of genes. We analyzed 20 sets of state biology standards at random to determine the nature of the standards in patterns of inheritance at the introductory biology or life science level in high school. Supplemental Table 1 at http://www.genetics.org/supplemental/ highlights four sets of these standards that provide a range of coverage of patterns of inheritance. A majority of these basic genetics/cell biology standards (15/20) included an examination of Mendel's laws of inheritance, some specifically describing the requirement to understand probability, Punnett squares, and the differences between autosomal dominant, autosomal recessive, and sex-linked traits. Other states included only more broad descriptions where a student would, for example, "Explain current scientific ideas and information about the molecular and genetic basis of heredity" (see supplemental Table 1). These are important data because they reflect the highly diverse nature of the level of detail required of students in U.S. high schools. While standards that fail to provide comprehensive detail allow talented teachers to provide creative and challenging learning opportunities for students, they can often also result in learning experiences that fail to

TABLE 6

Common misconceptions revealed in student essays

Theme	Quotation from student essay[a]	Correct conception
Genetic technologies	"When people who cannot have children and want their own from their own blood, meaning having their genes, what will stop them from putting some cells into a cow to get their child?"	This likely stems from the ideas that organs for potential transplant are being grown in different species. However, genetics as a field is not considering growing human embryos using other species as incubators.
	"Currently though there are some abnormalities in these animals being 'cloned' (cloned being that mammals cannot asexually reproduce but the technology in the science field today can do it for them. . . ."	Cloning in this sense actually refers to somatic cell nuclear transfer and does not refer to a reproductive technique for asexually reproducing organisms.
	"Similarly, in the germline gene therapy new genes would be added to the cells. With this it is possible that any trait can be added to an embryo and produce a "tailor made child". With more research more would be found about the human genome and the sooner parents would be able to select certain traits for a child, but this won't happen for a couple of decades."	The practice of eugenics as an acceptable technology in human reproductive technology ended decades ago. Moreover, this does not take into consideration the role of environment and other epigenetic factors in the development of specific attributes.
Patterns of inheritance	"If you were to have three chromosomes instead of the normal two, that child will have Down syndrome."	Humans have 23 pairs of chromosomes. Only an extra copy of chromosome 21 causes Down syndrome.
	"Half of your DNA is determined by your mother's side, and half is by your father. So, say, if you seem to look exactly like your mother, and had gotten all phenotypes from her, perhaps some DNA that codes for your body and how your organs run was copied from your father's genetic makeup."	Each cell in the body contains two copies of each chromosome, and therefore each gene, one copy from the mother and the other from the father. *Both* alleles may contribute to *all* attributes/traits that are genetically controlled. Moreover, most gene products (proteins) interact with other genes and do not act in isolation.
	"ADA is hereditary and must be inherited from both of the parents. . . . There is a 25% chance of having a child with ADA deficiency if neither parent carries the gene. There is a 50% chance of having a child with this disease if one parent carries the gene and the other doesn't. There is a 100% chance of having at least one child with ADA Deficiency if both parents are ADA positive. Two people with ADA Deficiency will almost definitely have at least one, or possibly more than one child who suffers from this disease. Some children of one parent with the disease will at least become a carrier, even if they never show any signs of having the disease. They can pass it on or have a child with the disease that is a dominant trait."	Adenosine deaminase deficiency (ADA) is caused by a mutation in a gene on chromosome 20 and is autosomal recessive. This means that to have the disorder, an individual must inherit a mutation in this gene from both the mother and the father. The chances of a child being diagnosed with ADA from parents that do not carry the mutation is extremely rare, $\ll 25\%$. If one parent is a carrier, there is only a 50% chance of the offspring also being a carrier. A carrier is does not experience any symptoms of an ADA patient. This is just one example of many of the recessively inherited disorders whose inheritance was not accurately described by students.
	"One study showed that chemical dependency skips a generation. This would make the gene for chemical dependency recessive. This means that if a psychiatric geneticist would make a Punnett square for two parents whose parents had chemical dependency, the Punnett square would say that 3 out of 4 of their children would be chemically dependant."	Chemical dependency is a complex trait that cannot be explained by a simple, monohybrid Punnett square cross.

(*continued*)

TABLE 6

(Continued)

Theme	Quotation from student essay[a]	Correct conception
Deterministic nature of genetics	"Genes determine everything form your sex, and hair color, to what diseases you many have and how high you will grow."	Genes are not necessarily deterministic. More frequently, environmental influences coupled with genotype determine phenotype.
	"If everyone on both sides of your family is tall, you are going to be tall. If half are tall and half are short, you have a 50/50 chance of being either tall or short. You also have the possibility of being somewhere in the middle."	This quotation appears to assume that single genes (perhaps taken from a simple Punnett square idea) determine height. Indeed, multiple genes, nutrition, and environment all play a role.
Nature of genes and genetic material	"All humans have DNA, as do animals, plants, and most bacteria and fungi."	All living organisms, including bacteria and fungi, have DNA.
	"Much like iodine is frequently added to the salt we consume, natural pesticides, extra vitamins, and longer life spans can be added to our fruits and vegetables."	Genetic modification of organisms is an extensive, lengthy process not analogous to the simple addition of a chemical.
Genetic basis of disease	"In the future knowledge about genetics could help stop deadly diseases and cancers. However this will only help with diseases that are hereditary."	Most illnesses have a genetic component without being hereditary. Therefore, a knowledge of genetics could have a much farther reach than this student recognizes. Indeed, the knowledge of the genetics of different viruses, for example, has resulted in vaccines for strains of influenza (Webby *et al.* 2004).
Genetics research	"If I could be a human genetics researcher I would study molecular genetics and how to alter it. One of the biggest problems to humanity is disease and if by studying DNA and the molecules that it is composed of, certain things could be stopped it would be well worth it."	While many geneticists study molecular genetics, they do so by focusing on a particular process, gene, or other aspect of this broader topic. Moreover, there is often a large gap between the basic research ongoing in molecular genetics and human disease prevention, treatment, and cure.
	"An experimental design I would like to try would to have people have the ability to hibernate in a frozen state, replicating the ability of the wood frog."	In the 2007 guidelines, students were asked to include their experimental design (see Table 4). Only 11% of students answering this question included any type of discussion on their experimental design. Moreover, students rarely exhibited understanding of a rational, reasoned approach to a testable hypothesis.
Reproductive technology	"Genetics create a perfect being. Change the genes. Make that child perfect. There's no better solution to an impending health care crisis. A perfect child means that health care can be focused on an aging generation of people. What we can have is a sea of people who all look brilliant, who are all smart and who all have perfect eyes, nose and lips. It's a perfect society, what more could we want?"	The goal of genetics, genetic research, and reproductive technology is not eugenic in nature. While scientists and clinicians indeed want to identify mutations that result in human illness for subsequent development of effective treatments (and potential cures), their ultimate goal is not to presume to name the traits that would be considered valuable in society.

[a] Quotations are copied directly from student text and not edited for correct grammar.

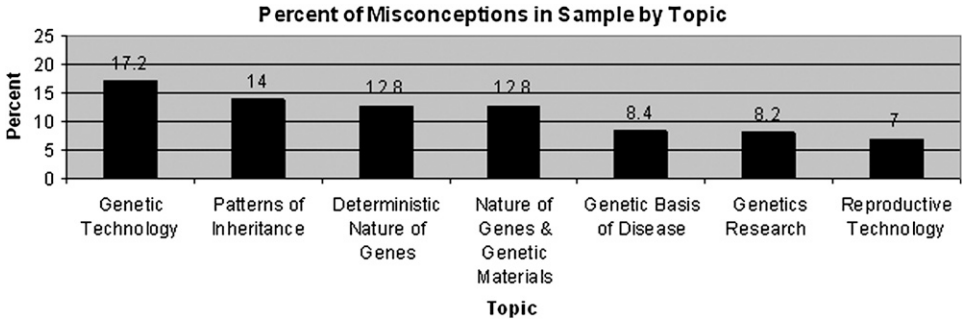

FIGURE 2.—Prevalence of misconceptions by genetics topic. A total of 500 essays were chosen at random (20% of total submitted) and were systematically reviewed for misconceptions. Frequently observed topics of misconceptions were identified and essays were cataloged on the basis of the type(s) of misconception(s) they revealed.

effectively teach students even the most basic concepts in biology.

Genetic technologies: The single greatest number of misconceptions identified from student essays could be broadly defined as falling into the category of "genetic technologies." When answering the question "If you were a genetics researcher, what would you study and why?" students often expressed their goal of curing multiple unrelated diseases. The reality is that most genetics researchers are often several steps removed from work on specific cures but instead devote their efforts to improving the molecular understanding of disease with the ultimate goal of improved treatments. Moreover, scientists generally study only one specific illness or class or related diseases. The work scientists currently perform to identify a disease-causing mutation is prominent in student essays with the common extrapolation to the "curing" of disease through gene replacement. Often, student essays also suggested that genetic engineering allows us to put a gene from any species into another species to have that trait expressed in exactly the same manner as in the original species. Students do not understand the complexity of biotechnology and genetic engineering. They make broad leaps without demonstrating an understanding for the multiple genetic and epigenetic (or environmental) factors that play a role in genetic regulation and manipulation of genetic materials in the laboratory setting. Moreover, there is a disconnect between observed characteristics and the physiological function of genes:

> We could eliminate all the premature deaths of people dying around the world from thirst if we genetically modified people to inherit some of the characteristics of the camel, allowing them to go for months at a time without drinking water.

Finally, we note the prevalence of essays that included information on the importance of stem cell research. While clearly a prevalent topic in the popular literature and press, students often discussed stem cell biology without ever discussing the *genetics* of stem cells. We did not include essays that included information on stem cells in our quantitative analysis. However, we note that scanning our database from 2006 for all references of "stem cells" revealed that almost one-quarter of essay submissions included this terminology without actively exploring the genetic nature of these cells despite the clear genetics-oriented nature of the essay questions.

Deterministic nature of genes: Another common misconception we observed is that one gene is always responsible for one trait or one gene with one mutation always causes one disease. The discovery of genes that convey and determine a specific phenotype is often displayed and hyped in the media. A cursory search of online news outlets yielded example headlines that could easily be misinterpreted, adding credibility to students' misconceptions. Some examples include the following titles: "Turning Off Suspect Gene Makes Mice Smarter" (nytimes.com, May 29, 2007) and "Researchers narrow search for longevity gene" (cnn.com, August 28, 2001). It is important for students to understand that it is rare that a single gene has complete control over an exhibited phenotype. Instead, multiple factors contribute to phenotype. Multiple genes often work together, with the environment, to determine ultimate phenotype. Our examination of standards revealed that only 3 of 20 state standards specifically mentioned that students should learn about polygenic inheritance (that more than one gene can contribute to a specific phenotype) and only 2 described the role of the environment in controlling phenotype. Thus, it is not surprising that we would see a common misconception that single genes are the cause of most traits and inherited diseases. Compared to the general nature of genetic inheritance, far fewer students would have necessarily been exposed to the concepts of non-Mendelian and polygenic inheritance.

Patterns of inheritance: Patterns of inheritance was another topic that revealed numerous misconceptions and misunderstandings of students. Not only were students often unable to correctly describe the nature of simple dominant and recessive patterns of inheritance, but also they were not able to go into any level of depth regarding genes or alleles, the physiological function of genes (proteins), or non-Mendelian patterns of inheritance. Some students even described genetic technologies as being able to "prevent the inheritance" of disease genes. Students focused primarily on simple Mendelian inheritance that was able to be analyzed via Punnett square analysis. All students described only monogenic traits that followed simple autosomal dominant, autoso-

mal recessive, or X-linked inheritance. Students were often unable to adequately describe sources of abnormal chromosome numbers. Essays did not mention errors during meiotic cell division and generation of gametes as the source of monosomies or trisomies. Our review of state science standards for high school students in biology suggests, not surprisingly, that the majority of states provide specific, detailed standards that mandate teaching students, even at the earliest levels of their life science education in high school, the basic biology of inheritance patterns. Although 15 of the 20 biology standards included basic patterns of inheritance knowledge, when we reviewed the essays that were cataloged as having an error or a misconception falling under "patterns of inheritance," 80% of those essays inaccurately described a basic tenet of Mendelian inheritance, despite their expected coverage of this material at their current grade level or in previous biology courses.

Nature of genes and genetic material: All 20 state standards examined require coverage of the nature of DNA as the hereditary material in living things. Nevertheless, students suggested that lower organisms, including bacteria and fungi, often do not carry DNA. We also noted student confusion regarding the hierarchal organization of genetic material. Notably, students were frequently unable to accurately define DNA, genes, and chromosomes. Often, these terms were instead used interchangeably. In 2007, $<1\%$ of essays included any information on additional genetic material in the genome. Students did not mention gene expression control elements, repetitive sequences (unless discussing Huntington's disease), or other nongene elements in the genome. Finally, students often described specific protein-encoding segments, or genes, as discrete elements that could easily be removed from one context and added in a separate context. While this view likely extends from students learning basic biotechnology and bacterial transformation techniques (for example, adding the green fluorescent protein from jellyfish to bacterial strains), likening this process to the adding of a chemical to a solution is an oversimplification, at best.

Genetic basis of disease: One of the principle errors observed in this category was the confusion of "hereditary" and "genetic" when describing diseases. In a small subset of cases, $\sim 10\%$ of the total essays categorized as having a misconception in this topic, students completely misrepresented the genetic nature of a specific illness (*e.g.*, calling HIV-1 an inherited disorder). While most illnesses have a genetic component, this does not make them hereditary. Moreover, while even infectious diseases can be considered to have a genetic component whether it be of the genetics of the virus itself or how individual genetics could result in different manifestations of the same illness, students must learn to clarify these differences. Cancer is a genetic disease. Only rare cancers, however, are hereditary. However, students often described breast and ovarian cancer as hereditary due to the mutations in BRCA1 or BRCA2. While mutations in these genes often do result in a cancer predisposition that appears to be inherited in a dominant-like fashion, the majority of breast cancer cases are not due to mutations in these genes.

Genetics research: A large number of student essays focused on the promise of genetic engineering in human health and reproduction (see also the *Reproductive technologies* section). While superficially this reflects that students recognize the positive influence that the study of genetics can have in their lives, numerous misconceptions suggest that students still fail to truly understand the nature and limitations of genetic research. An examination of state science standards, briefly described above, reveals that while state and national process (not necessarily content) standards require coverage of the nature of scientific research, inquiry, and discovery, this does not necessarily equate to students learning about how scientists actively perform research. Instead, these process standards reflect the fact that teachers are expected to provide students with opportunities for inquiry and investigation in the context of their own classroom laboratory experiments and activities. In short, state science standards do not require students to learn about the nature of scientific research.

Reproductive technologies: Misconceptions falling under the category of "reproductive technologies" could have been accurately cataloged under genetic technologies. However, this class of misconceptions was frequent enough to require special treatment. In these cases students continued to explore their ideas of genetic engineering and cloning to describe the future of reproductive control where prospective parents would "improve" and "design" their offspring, with the ultimate goal of having the "perfect" child. Eugenics, either in specific use of terminology or in concept, appeared in 15% of essays collected in 2007. This percentage is not reflective of the goals or ongoing work of genetics research. Unfortunately, its prevalence in student essays is likely due to both its historical role in research as well as the "genohype." Interestingly, the idea behind eugenics is not overtly described in the standards of any state science standards that we explored. The frequency of students describing using genetics to improve genotypes and design human beings, however, suggests that this is either the hook that teachers are using or the message that students are hearing from the media. More research would be required to determine which of these options is most prevalent.

DISCUSSION

Role of standards: State science standards are not the only source of direction for what is taught in public schools; textbooks, laboratories, statewide assessments, and teacher quality also play significant roles. These

benchmarks serve as the cornerstone of "standards-based reform," which has become prominent since the adoption of the "No Child Left Behind" legislation's requirement for stricter accountability of student achievement. After examining multiple state standards, it became clear that there is extreme variation between the levels of breadth and depth that individual states require of students at the same educational level (supplemental Table 1). Teachers rightly demand a balance between rigorous standards and flexibility, allowing them to establish creative and effective teaching methods. However, the current teaching environment makes it difficult for teachers to include information in the classroom not explicitly included in their state standards and therefore presumably their state content assessments. Thus, as states consider revisions of their next content standards in genetics, they should reevaluate their requirements in light of the body of literature that suggests that neither current standards nor current pedagogical methods being employed for conveying genetics to students are sufficient to produce enduring understanding of the material.

Misconceptions, scientific literacy, and genetic citizenry: Interestingly, many of the errors observed in the NAEP questions were also observed in our essays, reaffirming the wide-scale deficiency in genetics knowledge of high school students. While the data sets cannot be directly compared, it is of some concern that students in 2007 hold the same misconceptions as students in 2000 despite the rapid pace of advances in genetics technology and knowledge that occurred during that same period.

In genetics, anecdotal evidence from practitioners of high school life science (teacher e-mails and listserv communications) and direct evidence collected through these 2 years of ASHG-sponsored nationwide essay contests suggest that genetics is an area where many high school students harbor multiple misconceptions and significant misinformation. Some of this is likely due the exaggeration of the benefits and risks of genetics research and health information (Loo *et al.* 1998; Moynihan *et al.* 2000; Ransohoff and Ransohoff 2001). Students are clearly getting significant quantities of information from the Internet (most student essays referenced stories from a variety of different websites, but *not* from scientific references); students often rely on their teachers for ultimate validation of their information through discussions and grading. Scientists must work proactively with professional science writers to ensure that information in their field is accurately represented in the press. One study compared the text of original scientific articles with news reports about them (Ransohoff and Ransohoff 2001). Interestingly, these authors reported that when "hype" was identified in the popular press, it was the result of the original article and the scientists' own interpretations of their results.

Due to advances in genetic screening, genetic technology, the promise of individual genome sequencing, and other progress in the field of genetic research, it is more important than ever for the public to have a critical understanding of basic genetic information. This understanding will be vital for individuals to be informed advocates for their own health care when it comes to providing consent for testing and treatment as well as for being able to understand and interpret test results accurately. This will become an even greater need as private companies begin to provide genetic tests through mail order such that individuals can test themselves at home without the consultation of a physician (Advisory Committee on Genetic Testing 1998). For patients to understand the tests and results, and their own risk, they must be able to understand the biological underpinning of the tests themselves. Furthermore, as genetic research becomes more firmly embedded in medical practice and care, the public must be able to make informed decisions regarding specific pieces of legislation. Multiple studies, including this one, demonstrate that the current classroom methods for genetics instruction are not developing a citizenry with accurate mental models of inheritance and the genetic basis of disease (Henderson and Maguire 2000).

Similar to our analysis, work from Lewis and Kattmann (2004) reveals that students equate genotype and phenotype. Their work suggests that this is at least in part due to an incomplete understanding of genetic terminology. Other work suggests that acceptance of genetic determinism might negatively influence individual behavior and lifestyle choices. Believing a genetic illness is "something that is inherited that nothing can be done about," individuals may not heed the advice of clinicians to alter diet or behavior (Henderson and Maguire 2000).

Lack of precision in student writing results in difficulty in differentiating misconception from poor writing skills: Another significant observation we made after reviewing 2446 student essays is that students need to be instructed in writing with precision. In science, terminology and specialized vocabularies are important and can be problematic for students. Words used in everyday language can carry different meanings in science. Simply, it is clear that students are not being taught to write using technical language and appear to approach their scientific writing in the same way they might as an essay for an English or Social Studies assignment. For example, students often related that people "carry obesity" or that they have the "disease gene." But, neither of these is a precise description of the biological concept. Perhaps it is reasonable to extract that the first student meant that people "carry alleles that predispose them toward obesity" and the second student meant that a person with a genetic disease inherited a "mutation in a gene that caused a disease." But these inaccuracies leave us with the perception that students do not un-

derstand these intricacies in the language of science. While we can infer that a student understood a topic but was ineffective in the communication of that knowledge, this might be a leap that is ultimately damaging. Investigators have demonstrated that precise language usage appears even more important in scientific fields because it is not merely a vehicle for communicating understanding, but itself actively facilitates learning and comprehension (Connally and Vilardi 1989; Halliday and Martin 1993; Roth and Roychoudhury 1992, 1993; Rivard 1994). It is reasonable to suggest that writing-to-learn strategies that are successful in other disciplines and levels should be considered for inclusion in the high school science curriculum. Unfortunately, some work suggests that the adoption of writing across the curriculum programs—specifically those that engage students in scientific written discourse—is not widely used in the United States, despite success in Australia and the United Kingdom (Keys 1999).

Implications for undergraduate biology education: Another interesting observation from our work is that individual teacher knowledge, interest, and bias were clearly observed in student essays. Up to six students from a particular teacher could submit an essay to the contest. Frequently, similar themes were seen to run through many of the essays from a shared teacher–sponsor. For example, 3 essays in 2006 from the same teacher noted an interest in studying "gene doping." Yet, of the 2443 other essays collected over 2 years, not a single other essay mentioned this as a topic. Examples such as this reflect the critical influence individual teachers have on student interest, knowledge, comprehension, and possible misconception. Moreover, it is important to note that teachers were asked to submit their "top" essays. While it is impossible to determine if teachers vetted each essay prior to submission, it is reasonable to assume that many of the essays that were submitted were reviewed. Yet, 55.6% of essays reviewed exhibited a major misconception. This, in combination with the observation that student writing often clearly reflected specific information learned in the classroom, implies that student writing might be indicative of misconceptions held and perpetuated by the teachers.

This conclusion has important implications for instructors of undergraduate biology and genetics courses. Most high school biology educators receive their training in genetics through their undergraduate coursework in biology. Therefore, students are likely entering their undergraduate courses with these misconceptions and leaving with the same misconceptions. Our work should provide undergraduate science educators with the information they need to begin to eliminate the perpetuation of these misconceptions.

Responsibility of scientists for marshaling change: In addition to scientists recognizing these misconceptions when they direct their classroom agenda at the undergraduate level, this research calls on those practicing genetic research to adopt other changes in their communication about their research. Scientists must model accurate language and terminology usage when communicating to their peers, the press, and the community about their own work and the work of others. Genetics has a precise vocabulary (*e.g.*, it is a mutation in the cystic fibrosis gene, not the "cystic fibrosis gene," that results in a disease phenotype), and scientists must ensure that misconceptions are not perpetuated through their own misuse of these terms.

Another potential way for scientists to make significant inroads into correcting misconceptions at the K–12 level is to dedicate themselves to spending time in the classroom with teachers and students. Multiple programs offer the opportunity for scientists to mentor classroom teachers and students through either long- or short-term experiences. Indeed, many different scientific disciplinary societies foster such programs. Descriptions and information about these programs can be found at http://hub.mspnet.org/. Scientists can use these opportunities to promote accurate information to students and teachers about the nature of their discipline and scientific research. Unfortunately, this type of work is often viewed as secondary to professors' main responsibilities in their departments, especially in research-oriented departments. New programs must be developed to encourage, promote, and provide infrastructural support to scientists who dedicate themselves to this type of work. Indeed, the National Science Foundation has recently funded one such program currently sponsored by a scientific society (http://www.genednet.org/pages/GENA_about.shtml).

Challenges for change—Is it time to switch the paradigm? Gregor Mendel's work is clearly among the most important in genetics. However, the relatively simple view of one gene, one trait has yielded generations of students who can predict that "tt" will result in a small plant and "TT" will result in a tall plant. Unfortunately, this monogenic view of the world, while accurate for a small subset of characteristics, is clearly a limited one. While students that have an understanding of genetics consistent with a "Mendelian model" reflect a certain depth of understanding of genetic disease, can describe dominant and recessive patterns, and can grasp the concept of carrier *vs.* affected status (Henderson and Maguire 2000), the reality is that the nature of most traits and human disease is more complicated than this model. Only a minority of state standards require the coverage of alleles. Even in cases where dihybrid crosses are required per their inclusion in state standards, this still represents only monogenic inheritance of two separate traits (the tall, yellow pea plant *vs.* the short, green pea plant). But in the case of both traits, a single gene contributes wholly to the observed (height or color) phenotype.

Additionally, the requirement of teaching basic Mendelian genetics likely is a factor contributing to student

confusion regarding the deterministic nature of a single gene in phenotype control. For example, multiple students specifically selected human height as a character to explain how genetics is involved in phenotype. One example, also shown above, is "If everyone on both sides of your family is tall, you are going to be tall." Students take concepts of true-breeding plants (everyone being tall) and extrapolate them to human development. While we teach students that the genetic material is common between plants, animals, and humans, we must be careful to also teach them that genes and phenotypes are often under distinctly different molecular and biochemical controls in various organisms.

Despite multiple studies that have enumerated student misconceptions in genetics, no studies have shown that high school curricula have been altered to address these concerns. Additionally, little specific work has been done to determine the classroom curriculum that will most effectively address misconceptions in genetics. Some of the work currently being done in this area is through a program called the Geneticist–Educator Network of Alliances (GENA), a National Science Foundation-funded Math and Science Partnership program of the ASHG (http://www.genednet.org/pages/GENA_about.shtml). Several groups have performed extensive analyses of genetics curricula for the K–12 classroom. Reviews of genetics curricula can be found at (http://genetics-education-partnership.mbt.washington.edu/rev/revres.html and http://genednet.org/pages/GENA_CCRC.shtml). A number of challenges remain. The first is the question of how to reconcile data from a limited number of research studies that suggest that students do not retain information when taught in a traditional manner, relying on lecture to a prescribed curriculum (Kaufman *et al.* 1989). Then, once data are collected, compiled, and compared, how does one use that data to alter curriculum and textbooks to achieve better student understanding? Finally, while a number of individuals suggest that scientific education would benefit from a retooling that includes the requirement for students to learn information as it applies to their lives today and in the future, as well as the ability to evaluate scientific claims and information, this change is impeded by the need for districts, states, and even entire nations to demonstrate scientific content knowledge instead of deep conceptual understanding (Allen and Tanner 2003). Until significant research is performed by scientists and their educator colleagues that demonstrates which methods adequately teach both content and concepts, schools systems are unlikely to change their methods.

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