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Feature
Approaches to Biology Teaching and Learning

Making Biology Learning Relevant to Students: Integrating People, History, and Context into College Biology Teaching

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INFUSING SOCIAL CONTEXT IN BIOLOGY TEACHING

> *It is imperative that developmental biologists learn of the possible social consequences of their work and of the possible molding of their discipline by social forces. For today's biology students may be given more physical and social power than any group of people before them.*
>
> – Scott Gilbert and Anne Fausto Sterling

Biology is front page news, so it is important that we teach students to make connections between what they learn in the classroom and what they see in everyday life. As biology researchers, we recognize the negative implications of doing science in a vacuum as we are increasingly asked to communicate effectively with local and national legislators. As biology instructors, however, we may choose to teach biology devoid of social context, believing that students can make these connections on their own. But students model their instructors' behaviors, and follow their lead. If we integrate social issues into the biology curriculum, we model social responsibility for biology majors, and we demonstrate the need for biological literacy for nonmajors.

With an ever expanding biology curriculum, some instructors may wonder how they will find space to bring in social issues, and what biological content may be omitted in the process. By strategically embedding social context into those topics that are traditionally reviewed in multiple biology courses we sacrifice little time and content, and allow students to reflect on that social context more than once. By extending the Biological Concepts Framework (Khodar *et al.*, 2004) to issues of social relevance, we may improve student learning retention, since each concept has multiple points of entry, and therefore, multiple points of interest that can serve as avenues for the retrieval of information. Using real-world problems to thread a number of biological concepts together encourages students to move away from seeing biology as a collection of disparate concepts, subject areas, or chapters from textbooks that are far removed from society. This cues them to make connections to biology during their study of nonbiological disciplines. This approach leads to reinforcement of the social connection and to the development of a habit of mind that students can carry forward as they progress through a 4-yr curriculum and beyond.

Recent reports on science education reform promote this pedagogical approach because it prepares students to grapple with the interdisciplinary nature of twenty-first century problems (National Research Council [NRC], 2005). Integrative learning is listed as one of four essential learning outcomes in the "Learning for the New Global Century report." The "Integrative Learning Project," initiated by the American Association of Colleges and Universities (AAC&U; 2007) and the Carnegie Foundation for the Advancement of Teaching, provides practical resources for achieving these goals (AAC&U and Carnegie Foundation, 2007). This shift in emphasis from disciplinary to integrative learning stems from research in cognitive science that demonstrates how students' previous knowledge can influence how they organize and link new information, constructing "schemas" that are deeply rooted in personal and cultural experiences (Vygotsky, 1978; Ausubel *et al.*, 1978; Lattuca *et al.*, 2004). With this in mind, this feature first demonstrates the important connection between biology and social issues, and then examines how the history of biology can be used to infuse relevance into the biology curriculum.

CONNECTING BIOLOGICAL CONTENT KNOWLEDGE TO SOCIAL ISSUES

Stories that focus on the people of biology remind students that biological research is a human endeavor and, like any

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other, is not isolated from politics, social norms, or the paradigms of the time. The following section demonstrates how familiar biological topics, such as sickle cell anemia, gene regulation via the lac operon, and energetics can be presented within their social contexts. These examples are followed by a summary of large-scale efforts and tables listing resources to assist instructors in this integration process.

Sickle Cell Anemia: Multiple Points of Connection

Though sickle cell anemia (SCA) is used to illustrate a variety of complex biological concepts in a variety of courses (genetics, evolution, biochemistry, physiology), few biology courses place this topic in broad social context. Developmental gene regulation, genotype–phenotype relationships, protein polymerization, cooperative binding, and balanced polymorphisms as they relate to evolution can all be illustrated using SCA as an example. But without the social context, students may leave the classroom with misconceptions about allele frequency and distribution, and believe that these concepts are of little importance in the real world. We can use the social history surrounding the development of the molecular diagnostic for SCA and its subsequent use in genetic screening programs in the United States as a vehicle to teach these biological concepts. By doing so, we strengthen the connection between these different biological concepts, and we also demonstrate how biology taken out of social context can lead to widescale social injustice.

To understand how biology instructors might use SCA genetic testing programs to contextualize basic biological principles and concepts, we must first take a look at the social issues that have surrounded these programs. Legislation for SCA genetic screening has shifted over the last 40 years from mandatory state laws, to a voluntary national program, to genetic testing of employees by government employers without informed consent (Bowman, 1977; Markel, 1997). In all of these cases, the target population for screening is African American, despite the fact that the sickle cell allele is not restricted to this racially defined group (Markel, 1997). This misconception was furthered by statements made by President Nixon when he reasoned in 1972 that the National Sickle Cell Control Act was necessary to eliminate a neglected disease that "strikes Blacks and no one else" (Nixon, 1972; P.L. 92–294). Though the Black Panther Party fully supported the SCA Control Act, believing that it would promote better health in their communities, the Act resulted in mass discrimination against African Americans in the United States, many of whom lost health and life insurance, access to public schools, and jobs (Culliton, 1972; Bowman, 1977). This screening program serves as one of the best historical examples of a genetic test gone wrong and continues to haunt African Americans today, as it is maintained on the New York state marriage license application (13aa) and has surfaced in court cases surrounding genetic testing in the workplace (Bowman, 2000; Carroll and Coleman, 2001; Louisana State University, 1998; *Norman-Bloodshaw v. Lawrence Berkeley Labs*, 135 F3d 1260, 9th Circuit, 1998).

Perhaps surprising to scientists is that Nobel Laureate Linus Pauling, one of the pioneers involved in establishing the first molecular test for SCA, was an advocate of the screening programs that resulted in discriminatory practices. Most scientists remember Pauling as a staunch dissenter of nuclear energy research because of its potential to cause human suffering. On the issue of SCA screening and family planning, Pauling believed here, too, that he could prevent human suffering, as demonstrated by the following quote:

> *There should be tattooed on the forehead of every young person, a symbol showing possession of the sickle cell gene [so as to prevent] two young people carrying the same seriously defective gene in single dose from falling in love with one another.*
>
> – Linus Pauling (Markel, 1997)

To include Pauling's position in our teaching is important for a number of reasons. By acknowledging this history, we can examine how biological discoveries and their applications can be shaped by social prejudices of the time (Table 1, SCA). We also illustrate how Pauling's reputation as a scientist and, thus, a person of authority, was used by others to support a policy that resulted in social injustice. In asking students to analyze Pauling's quote, we encourage them to consider what role they will play in communicating and situating their work in the public domain. This is particularly important to the SCA case, as many healthcare providers were unaware of their misunderstanding of the molecular biology behind the SCA diagnostic, which resulted in miscommunication of disease status. This confusion was partly due to a shift from cytological screening to molecular screening via hemoglobin solubility assays. Because physicians were not accustomed to viewing phenotypes at both the molecular and organism level, nomenclature became problematic. The government, the medical community, and the general public began to conflate the carrier status of "sickle cell trait" with sickle cell disease (Markel, 1997).

These biological misconceptions serve as an excellent segue for class discussions or lectures focused on allele frequency, inheritance patterns, and genotype–phenotype relationships (Strasser, 1999). Students are often surprised to learn that the SCA allele can follow a recessive, dominant, or incomplete dominant inheritance pattern depending on the phenotypic assay (anemia, malaria resistance, or solubility, respectively). Reminding students that malaria acts as an environmental agent for the selection of the protective SCA allele reminds students that the distribution of alleles is not a result of race, but environment. Analyzing data from the hemoglobin molecular solubility test addresses the need for a full understanding of the genotype–phenotype connection and the need for appropriate nomenclature. This biological analysis of the SCA story teaches students to question experimental results and interpretations in the face of new knowledge and technologies. By integrating the biological and the sociological perspectives of the SCA genetic screening program, we make the biochemistry of hemoglobin and the genetics of β-globin meaningful both inside and outside the biology classroom.

The Lac Operon and Energetics: The Evolution of New Products

The social history of SCA screening programs resonates with the diverse undergraduate population of the United States, but serves as only one example of how contextualization of biology curricula can be achieved. Another example that is pervasive in the biology curriculum is the lac operon. Though we ask students to understand the detailed regulation of this operon, its significance is often not clear for students, though many social connections exist. The high frequency of global lactose intolerance can serve as a jumping-off point for discussions about developmental gene regulation in the infant and the adult, different evolutionary outcomes for adult lactase expression based on the domesticated livestock practices of Northern Europeans and some African tribes, and the emergence of probiotic products designed to address the lactose intolerance phenotype of some individuals (Gibbons, 2006; Tishkoff *et al.*, 2007; Stanford University, Human Biology Core Course, www.stanford.edu/dept/humbio/cgi-bin/?Q=node/177).

By juxtaposing prokaryotic and eukaryotic lactase expression in this context, students gain a more comprehensive understanding of gene regulation and are less likely to confuse the two, or perhaps may even see where they share structural similarities (operons and miRNA precursor clusters).

Table 1. Resources for the people of biology

Women and Minorities in Science
African American Scientists. Science Update. AAAS. www.scienceupdate.com/spotlights/africanamerican.php (accessed 8 March 2008). *Audio and print summaries of biographies.*
African American Scientists. The Faces of Science: African Americans in the Sciences. https://webfiles.uci.edu/mcbrown/display/faces.html#Past (accessed 8 March 2008). *Database of individuals searchable by profession or name; biographies are short but list of references and video are rich.*
African American Female Scientists. Warren, W. (1999). Black Women Scientists in the United States, Bloomington: Indiana University Press. *Collection of biographies.*
Biographies/Movies/Websites. Morris, T. E., and Gal, S. (2003). A Recipe for Invention: Scientist Biographies, National Center for Case Study Teaching in Science. www.sciencecases.org/sci_bios/sci_bios.asp (accessed 8 March 2008). *Science case study that builds on education research ("Draw A Scientist") and has links to many databases of biographies, movies, and websites.*
Biology/Politics. Brady, C. (2007). Elizabeth Blackburn and the Story of Telomeres: Deciphering the Ends of Chromosomes, Boston: MIT Press. *Reviews Blackburn's contributions to biological research, her experience as a female scientist, and her role in the politics of stem cell research.*
Minorities in Science. SACNAS Biographies Project. Society of the Advancement of Chicanos and Native Americans in Science www.sacnas.org/biography/default.asp (accessed 8 March 2008). *Collection of biographies designed for high school level; searchable by gender, ethnicity, name, or subject.*
Nobel Prize Women. McGrayne, S. (1993). Nobel Prize Women in Science. Their Lives, Struggles, and Momentous Discoveries, 2nd Edition. Washington, DC: National Academies Press. www.nap.edu/catalog.php?record_id=10016 (accessed 8 March 2008). *Biographies of female scientists who make up only 3% of all Nobel Prize winners.*
SCA/Biochemistry/Biography. Eugenics for Alleviating Human Suffering. (1970). In: It's in the Blood! A Documentary History of Linus Pauling, Hemoglobin, and Sickle Cell Anemia. SUNY, NY, November. Special Collections, Valley Library, Oregon State University. Produced by Jason Hughson. http://osulibrary.oregonstate.edu/specialcollections/coll/pauling/blood/narrative/page35.html (accessed 8 March 2008). *Notes, excerpts, audio and transcripts from Linus Pauling's writings and presentations.*
Women In Plant Biology. www.aspb.org/committees/women/pioneers.cfm (accessed 8 March 2008). *Biographies of female plant biologists; includes McClintock and Margulis.*
Women in Science. San Diego Supercomputing Center. *Sixteen biographies that detail the personal journey of female scientists; includes Rosalind Franklin, Roger Arliner Young, and Mary Anning.*
Professional Societies and Award-Granting Organizations
ASCB Member Profiles. www.ascb.org/index.cfm?navid=79 (accessed 8 March 2008). *Collection of member profiles dating back to 1992; includes both personal and career driving moments of success.*
Biology. Judson, H. F., Tobias, P., Rogal, L., Crick, F., Berg, P., Karn, J., Hodgkin, J., Tan, C., and Brent, R. (2002). Going Strong at 75. The Scientist *16,* 16. www.the-scientist.com/article/display/12927 (accessed 8 March 2008). *Collection of articles written by scientists about Sydney Brenner; traces his maturation as a scientist and influential leader of science.*
EMBO: Science & Society Interviews Archives. www.nature.com/embor/archive/interviews/2001.html (accessed 8 March 2008). *Collection of 3–5 interviews each year since 2000 with prominent scientists speaking about the implications of their work and the role of science in a global context (must scroll down to Science & Society section).*
EMBO: At the Benches. www.embo.org/communities/benches.html (accessed 8 March 2008). *Short essays outlining the lives of young scientists at different stages of their careers in industry and academia.*
Genetics Society of America: Conversations in Genetics. www.genestory.org/index.html (accessed 14 July 2008). *Collection of biographies and film clips of geneticists interviewed by other geneticists.*
JBC: Reflections. www.jbc.org/cgi/sectionsearch?tocsectionid=Reflections (accessed 8 March 2008). *Reflections are invited articles by respected biochemists that chart career trajectories.*
Microbiology. Meet the Scientists, Microbe World. American Society for Microbiology. www.microbeworld.org/scientists/interviews/Liis-annePirofski.aspx (accessed 8 March 2008). *Fourteen interviews with microbiologists and researchers in public health.*
Nobel Prize.org. http://nobelprize.org/nobel_prizes/medicine/articles/golgi/index.html (accessed 8 March 2008). *Biographies and history of discoveries in science.*
PNAS Profiles. www.pnas.org/cgi/collection/profiles (accessed 8 March 2008). *Collection of 139 scientists' profiles.*
The Scientist: Profiles. www.the-scientist.com (accessed 8 March 2008). *Profiles of junior and senior researchers including personal insight; searchable by science journalist of the series, Karen Hopkin.*

They will also learn that though prokaryotes and eukaryotes evolved different mechanisms of genetic control, human consumption of milk and probiotics can influence gene regulation (Enattah *et al*., 2002). Examination of these macro-scale environmental conditions highlights the intimate connection between genes and environment (Wade, 2006). This connection can be placed within the larger biological conceptual framework of combinatorial control, by revisiting SCA experimental treatments that exploit the natural developmental shift from β-globin fetal gene expression to adult β-globin gene expression. By juxtaposing the SCA and lactase examples, students become better able to recognize common themes such as environmental influence on gene expression and to consider different levels of environmental scale.

Instructors could delve deeper into the social implications of biological knowledge by pointing to the recent development of DNA tests for lactose intolerance, or lawsuits brought against Dannon for false advertising associated with their probiotic yogurt products (Business Wire, 2008, Wade, 2002). Here, instructors can highlight the work of members of the American Society of Microbiology who released a report titled "Probiotic Microbes: The Scientific Basics" that was used in litigation against Dannon.

This report illustrates the social responsibility of professional science organizations. Integrating the report into a biology curriculum allows students to explore the allegations from the biological perspective, provides them with an opportunity to apply knowledge learned, and encourages them to pay attention to the interplay between biology and society (Walker and Buckley, 2006).

Another common biological subject area is energetics. Here, too, students may memorize the metabolic by-products of glycolysis and respiration, but never understand why these pathways are important to other subject areas such as oncogenesis. Instructors can point to the relevance of energetics by using a PET scan image to demonstrate how cells respond to their environments. Cancer cells devoid of blood-flow increase glucose uptake as they switch from respiration to glycolysis in an effort to compensate for the lack of oxygen and in response to the less efficient ATP production via glycolysis. Understanding why some tumors promote the development of blood vessels, while others do not, relates back to the relationship between genes and environment. Students can connect this material to the larger biological concept of environmental control of gene expression at yet another level of scale—that of the localized extracellular environment. The social connection can be extended by pointing to Judah Folkman's work on angiogenesis and the subsequent development of anticancer drugs based on this work (Wade, 1997).

The above examples illustrate how biology instructors can take traditional topics and place them in historical and contemporary context, bringing in other important overarching biological concepts such as evolution and gene–environment interactions, while highlighting the work of significant figures in the field of biology.

Large-Scale Efforts to Infuse Social Context into Biology Teaching

A number of institutions have used the approach of highlighting the relevance of biology to everyday life in an effort to influence students' choice of majors and careers. Tribal colleges, such as Oglala Lakota College and the Universidad Metropolitana (Puerto Rico) were selected as Model Institutions of Excellence by the National Science Foundation (NSF), increasing their graduation of science, technology, engineering, and mathematics (STEM) majors by 44% over a 10-yr period. This was accomplished by developing courses that orient the curriculum to local place and culture (Amber, 1998; NSF, 2007). In a similar effort, faculty at Evergreen State College, Longhouse, developed "The Enduring Legacies Native Cases" that have a strong focus on land rites, indigenous knowledge, and environmental sciences (Enduring Legacies Native Cases, www.evergreen.edu/tribal/cases/index.htm). Whittier College requires all undergraduates to complete a three-semester math and science sequence that culminates in a capstone course titled "Math and Science in Context," which is focused on global problems and prepares students to be informed citizen-leaders (Whittier College, www.whittier.edu/oldsite/science-math/default.htm). In 2001, an international effort to bring together scientists interested in connecting their work to societal problems was initiated by members of Science Education for New Civic Engagements and Responsibilities (SENCER). Members have developed model courses for majors and nonmajors that are disseminated through their website, a newsletter, faculty development workshops, and more recently through a fellows program (SENCER, 2008). Collectively, these efforts strive to produce citizen-biologists and galvanize students to take an active role in promoting biological research as they move through their careers (Table 2).

USING THE HISTORY OF BIOLOGY TO HIGHLIGHT SOCIAL CONTEXT

To help students understand that biological research can be influenced by people within the scientific community as well as outside of it, instructors can use the history of biology to provide context for the development of key principles, methods, and concepts. By tracing the steps of discovery through time, students see that biological knowledge is the result of human activity with each researcher building on the other's work through communication, competition, and collaboration. Though students might struggle to embrace a lengthy and nonlinear path of biological discovery, they may also be comforted by the fact that each discovery was not achieved alone. By sharing the history of biology with students, we present a more realistic view of the construction of biological knowledge: Opposing hypotheses or conflicting results are common; the paths of discovery can involve technological limitations, experimental challenges, missteps, and wrong turns; and culture and politics can influence the direction of research. By sharing historical tales of discovery, we promote the development of critical thinking through the creation of learning environments in which students feel comfortable airing misconceptions of their own, taking risks, and asking questions.

The History of Evolutionary Theory

A careful selection of topics from the historical record can be used to enhance student learning, but since time and

Table 2. Resources for biology in social context

Case Studies, Problems, Pedagogy
Case Studies in Biology (book). Waterman, M. A., and Stanley, E. D. (2005). Biological Inquiry: A Workbook of Investigative Case Studies, San Francisco, CA: Benjamin Cummings. *Collection of cases that place biology in context.*
Case Studies in Science (book). Herreid, C. F. (2007). Start with A Story. The Case Method of Teaching College Science, Arlington, VA: NSTA Press. *Collection of articles and strategies for teaching with case studies.*
Case Studies in Science (online). National Center for Case Study Teaching in Science. C. F. Herreid and N. Schiller, Directors, State University of New York at Buffalo Case Collection. http://ublib.buffalo.edu/libraries/projects/cases/case.html (accessed 8 March 2008). *Clearinghouse for case studies organized by discipline and author; teaching notes, assignments, and password-protected answer keys provided.*
Problem-Based Learning (online). University of Delaware. Problem-Based Learning Clearinghouse. www.mis4.udel.edu/Pbl/index.jsp (accessed 8 March 2008). *Clearinghouse for problems in social context.*
Science Education for New Civic Engagements and Responsibilities (online). www.sencer.net (accessed 8 March 2008). *Collection of model course curricula, articles, newsletter, summer institutes, and regional conferences.*
Books
Bioscience. Franklin, S., and Lock, M. eds. (2003). Remaking Life and Death: Toward an Anthropology of the Biosciences, Santa Fe: School of American Research Press. *Collections of essays on various aspects of cell biology including apoptosis, transgenic organisms, cloning, genetic enhancement, biodiversity of microbes, and stem cell therapy.*
Developmental Biology and Genetics. Gilbert, S., Tyler, A., and Zackin, E. (2005). Bioethics and the New Embryology: Springboard for Debate, New York: Sinauer Associates. *Companion text developed by Scott Gilbert and his students in freshman seminars at Swarthmore College; each topic is addressed by coordinating chapters that address the social and scientific perspectives.*
Genetic Nature/Culture. Goodman, A, Heath, D., and Lindee, S., eds. (2003). Genetic Nature/Culture: Anthropology and Science beyond the Two-Culture Divide, Berkeley: University of California Press. *Collection of essays in anthropology and history focused on biodiversity in humans and animals, pedigree analysis, national genomic databases/informed consent/privacy, genetically modified organisms, and genetic enhancement.*
Genetics and Genomics. Wexler, A. (1996). Mapping Fate: A Memoir of Family, Risk, and Genetic Research, Berkeley, CA: UC Press. *Memoir that details the story of Nancy Wexler's search for the Huntington's gene through the eyes of her sister Alice Wexler.*
Genomics and Art. Kevles, B., and Nissenson, M. (2000). Picturing DNA. www.genomicart.org/genome-toc.htm (accessed 8 March 2008). *Book chapters address genes and justice issues using artwork from the "Paradise Now" exhibit, scientific summaries, and artist interviews.*
Genomics History and Social Implications. Sloan, P., ed. (2000). Controlling Our Destinies: Historical, Philosophical, Ethical, and Theological Perspectives on the Human Genome Project, Notre Dame. IN: Notre Dame Press. *Collection of essays and responses from a conference at Dartmouth funded in part by the DOE ELSI in 1995.*
Journals
Biology and Medicine. Perspectives in Biology and Medicine. ProjectMuse. http://muse.jhu.edu/journals/pbm (accessed 8 March 2008). *Interdisciplinary journal places subjects of current interest in context with humanistic, social, and scientific concerns; neurobiology, biomedical ethics and history, genetics and evolution, and ecology.*
Developing World Bioethics. Blackwell Publishing. www.blackwellpublishing.com/journal.asp?ref=1471–8731 (accessed 8 March 2008). *Journal dedicated to providing a more global view of bioethics; collection of freely available highlights; specific focus on HIV/AIDs, indigenous knowledge and resources, and cultural practices.*
Kennedy Institute of Ethics. The John Hopkins University Press. http://kennedyinstitute.georgetown.edu/publications/kie_journal.htm (accessed 8 March 2008). *Forum for diverse views on bioethics, including feminist perspectives; includes "Scope Notes," an overview with extensive annotated bibliography on specific bioethics topics; includes "Bioethics at the Beltway" for insider information on activities at the federal level; some volumes are dedicated to stem cell research as it relates to oocyte donation, cultural diversity, and public–private ventures.*
Science as Culture. New York: Routledge. *Published four times per year; dedicated to the analysis of culture values as seen in facts, artifacts, processes, designs, weapons, and wonders from the field of science and technology; i.e., article by MacPhail on the Viral Gene provides a historical and cultural view of transposable elements in the human genome.*
SEED: Science as Culture. Seed Media Group LLC. http://seedmagazine.com/magazine/ (accessed 8 March 2008). *Magazine that connects science to society and art; similar to* Wired Magazine *in format and contemporary coverage; includes "Pharyngula" column authored by PX Meyers and focused on evolutionary biology; includes "Seed Salon," conversations between leaders in the field of science and art/design.*
Websites and Video
Cell Biology. Chamany, K. (2004). Cell Biology for Life, New York: GarlandScience. www.garlandscience.com/textbooks/cbl (accessed 8 March 2008). *Curriculum placed in contemporary and historical social context; primers linked to primary literature focused on stem cell research, botulinum toxin, and HPV and cancer; more resources listed in the references section of each module.*
Developmental Biology. Companion website for Developmental Biology textbook, Sunderland, MA: Sinauer Associates. http://8e.devbio.com/keyword.php?kw=bioethics (accessed 8 March 2008). *Collection of white papers on ethical and historical dimensions of stem cell research with videos and animations.*

Table 2.—*Continued*

Epigenetics. Ghost in Your Genes. (2007). NOVA/WGBH. Holt, S. and Paterson, N. www.pbs.org/wgbh/nova/genes (accessed 8 March 2008). *Freely available video clips focus on the role of social and environmental factors on gene expression and inheritance.*
Genetics. Dolan DNA Learning Center. Gene Almanac, Cold Spring Harbor. www.dnalc.org/ddnalc/websites (accessed 8 March 2008). *Enhanced Eugenics Image archive; DNA from the Beginning History archive; link to genes and health; laboratory experiments focused on bioinformatics.*
Genetics and Identity. Genetics Identity Group. www.ahc.umn.edu/bioethics/genetics_and_identity/index.html (accessed 8 March 2008). *Collection of case studies, papers, and resources that examine the use of DNA identification to establish inclusion or exclusion to a racial or cultural group.*
Genomics. Cracking the Code of Life. (2001). Produced by Arledge, E. and Court, J. NOVA/WGBH/Clear Blue Sky. www.pbs.org/wgbh/nova/genome/program.html (accessed 8 March 2008). *Freely available video clips that demonstrate the interconnection among genetic technologies, genomic knowledge, and applications in society.*
Infectious Diseases/Biotechnology/Indigenous Knowledge. Science and Development Network. www.scidev.net/en (accessed 8 March 2008). *Collection of white papers on range of topics including neglected diseases, genetically modified organisms, regulation of biotechnology, conservation, and climate change; searchable by geographic area or subject.*
Public Health. Rx for Survival. (2005). Nierman, M., Senior Producer. WGBH Educational Foundation and Vulcan Productions, Inc. www.pbs.org/wgbh/rxforsurvival (accessed 8 March 2008). *DVD series with some video clips freely available on website; neglected diseases and technologies to address them; historical and contemporary overview of antibiotics, vaccines, clean water, and nutrition.*

Table 3. Resources for the history of biology

Books

Cancer Biology and Immunotherapy. Bazell, R. (1998). HER-2: The Making of Herceptin, a Revolutionary Treatment for Breast Cancer, New York: Random House. *A biography of a molecule, tracing the history of its discovery*
Cancer Biology. Weinberg, R. (1999). One Renegade Cell, New York: Basic Books. *Exciting historical narrative of early theories and paradigm shifts in cancer biology.*
Cell Biology. Rensberger, B. (1998). Life Itself: Exploring the Realm of the Cell. Oxford. *Journalistic account of discoveries in cell biology originally published as front page series in the* Washington Post.
Developmental Biology. Keller, E. F. (1995). Language and Science: Genetics, Embryology, and the Discourse of Gene Action. In: Refiguring Life: Metaphors of Twentieth Century Biology, New York: Columbia University Press. *Brief monograph that describes the historical shift from embryology to genetics and the way that discipline-based metaphors have directed scientists' search for evidence.*
Evolution. Young, R. M. (1985). Darwin's Metaphor: Nature's Place in Victorian Culture. http://human-nature.com/dm/dar.html (accessed 8 March 2008). *Philosopher's critical synthesis of history, politics, and ideology, viewed through six inter-related essays written between 1968 and 1973.*
History of Biology. Journal of History of Biology. Springer. www.springer.com/philosophy/philosophy+of+sciences/journal/10739 (accessed 8 March 2008). *Pays particular attention to developments during the nineteenth and twentieth centuries; appropriate for the working biologist and the historian.*
Microbiology and Immunology. De Kruif, P. and Gonzalez-Crussi, F. (2002). Microbe Hunters, Orlando, FL: Harcourt (originally published in 1926). *Collection of 12 fictionalized historical accounts of microbiologists on the brink of discovery, including Leeuwenhoek, Pasteur, Koch, Ehrlich, Roux, and Metchnikoff; some inappropriate discriminatory remarks due to the time period, and instructors should forewarn students of these passages.*
Molecular Biology. McCarty, M. (1986). The Transforming Principle: Discovering that Genes Are Made of DNA, New York: WW Norton. *Firsthand account of the seminal experiments that led to the discovery of DNA as heredity material.*
Stem Cell Biology. Maienschein, J. (2003). Whose View of Life. Embryos, Clones and Stem Cells, Harvard University. *Historian's account of the history of cell biology, stem cell research, and legislation governing embryo research.*

Websites and Video

Cell Biology. Sardet. C. (2007). Exploring the Living Cell, New York: GarlandScience and CNRS Images. *DVD with early drawings and film tracing the history of cell biology research.*
Cell Biology. Matveev, V. *et al*. The Discovery of the Cell. BioMedES. www.ifcbiol.org/Dotcweb/index.html (accessed 8 March 2008). *Comprehensive history of cell biology and cell theory, collaboratively constructed with a strong focus on historiography. Color coding highlights, key moments in history, concepts important to the field, and areas of controversy.*
Embryology. Arizona State University. The Embryo Project Encyclopedia. http://embryo.asu.edu/encyclopedia/search.php (accessed 8 March 2008). *Collection of images, concepts, people, books, and critical essays pertaining to the field of embryology that display relationships as maps (see EP Topics).*
Evolution. UC Berkeley. The History of Evolutionary Thought in Understanding Evolution. http://evolution.berkeley.edu/evolibrary/article/0_0_0/history_01 (accessed 8 March 2008). *Curriculum, timeline superimposed with four different disciplinary perspectives on the history of evolutionary concepts.*
Evolution. PBS. (2001). Evolution for teachers. WGBH Foundation. www.pbs.org/wgbh/evolution/educators/index.html (accessed 8 March 2008). *Curriculum, short videos, links to historical texts designed to teach evolution.*
Molecular Biology. Oral Histories: Program in the History of Biosciences and Biotechnology. Archive of California. http://content.cdlib.org/xtf/view?docId=kt6q2nb1tg&brand=oac&doc.view=entire_text (accessed 8 March 2008*). Oral histories full of personal details and insider information via interviews with the early pioneers of rDNA technology; includes Boyer, Kornberg, Berg, Cohen, and others, searchable by name or keyword.*
Philosophy of Science. Pantaneto Forum. www.pantaneto.co.uk (accessed 8 March 2008). *Collection of articles that promote debate on how scientists communicate, with particular emphasis on better philosophical understanding of science.*

space are limited in our courses, we must be judicious in our choices. In 2003, a working group of biologists was asked to define four or five central biological concepts that should be taught in every undergraduate biology course for the Steering Committee on Criteria and Benchmarks for Increased Learning from Undergraduate STEM Instruction (NRC, 2003). After many hours of deliberation, the group reported that evolution was the only concept common to all biology courses, and that other concepts (i.e., germ theory, cell theory, energetics, the central dogma) should be taught in courses that specifically require this knowledge. Given this outcome, it seems that it would be wise to teach the historical development of evolutionary theory, as this theory is the foundation of all of biology.

Though most biology educators have no formal training in the history of biology, we are fortunate to have access to many resources that highlight the significant events and people that have shaped evolutionary thought. Excellent sources that critically evaluate the contributions of scholars to the theory of evolution include "Evolution for Teachers" produced by PBS, the "Understanding Evolution" project hosted by The University of California (UC) at Berkeley, and Robert Young's online book *Darwin's Metaphor: Nature's Place in Victorian Culture* (Table 3). These resources acknowledge that ideas from other disciplines were essential to the development of evolutionary theory. The UC Berkeley site offers a concept map superimposed over a timeline that demonstrates the four disciplinary areas that contributed to our current understanding of evolution. In Young's book, excerpts from Darwin's *Origin of the Species*, Charles Lyell's *Principles of Geology*, and Thomas Malthus' *An Essay on the Principle of Population* are analyzed for commonalities. By viewing these excerpts together in one text, students learn that though Darwin was focused on the process of animal speciation, it was Malthus' work on economics and the social condition that ultimately propelled Darwin to make the leap from artificial selection to natural selection. Social philosopher Herbert Spencer then adapted the concept and coined the phrase "survival of the fittest" in *Principles of Biology* published in 1864. These resources naturally lead to conversations about "Social Darwinism" and the subsequent development of social eugenics practices in the United States, which can be illustrated by images from the "Eugenics Image Archive" hosted by the Dolan DNA Learning Center (Table 3). As evolution is the one guiding principle of all of biology, it is important that students be aware of the historical underpinnings of this theory, and recognize that even today there is debate about which biological phenomena contribute the most to speciation. The latter topic is brought to view more directly in a recent book that focuses on the contributions of horizontal gene transfer (Margulis and Sagan, 2003).

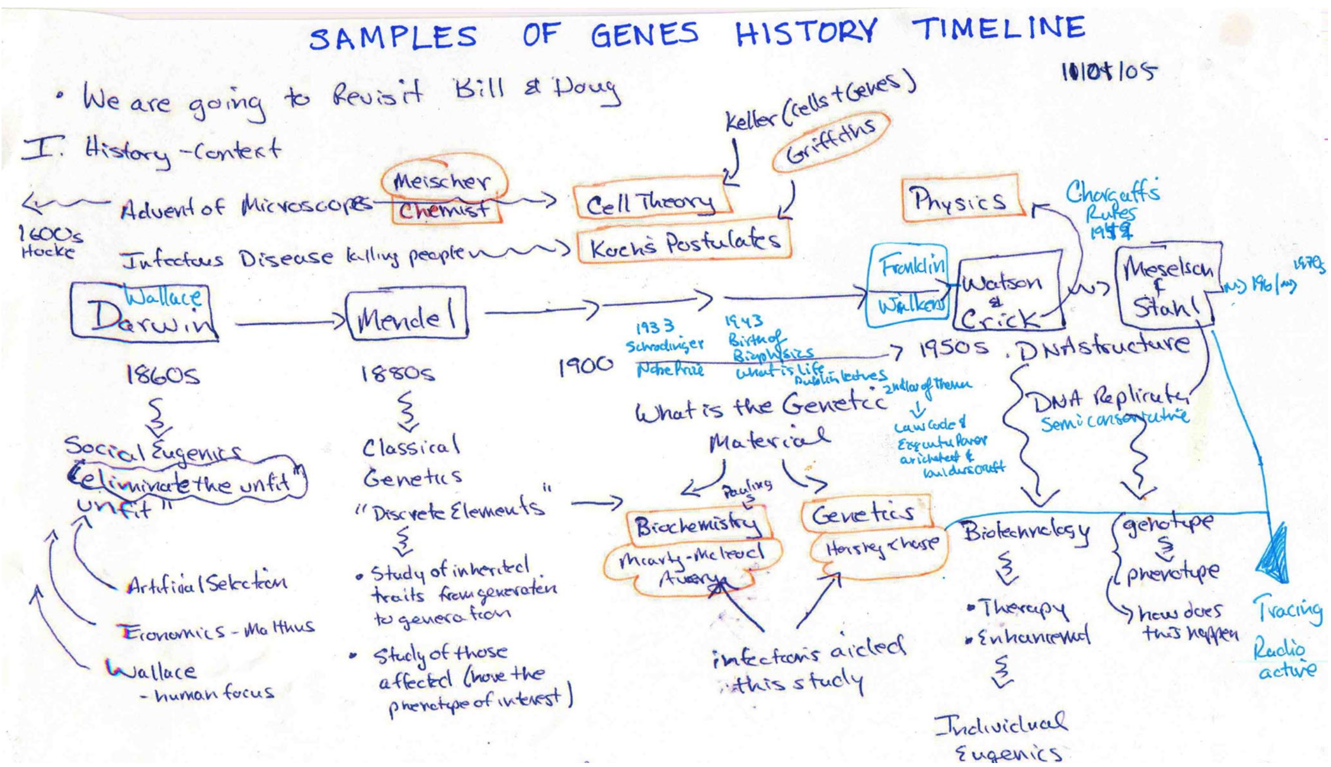

Figure 1. Example of a class-constructed genetics timeline. This image was constructed in one class session of an introductory genetics course in which students were asked to integrate the people, history, and experiments that led to an understanding of DNA as the transforming material. Events and publications from physics, chemistry, and biology are woven together; common techniques of the time are highlighted, including the use of radioactivity to trace molecules undergoing various molecular processes. The nod to "Bill and Doug" refers to a parable that helps students discern the differences between biochemical and genetic approaches and the merits of both in solving problems (Kellogg, 1994; Sullivan, 1993). There is a strong emphasis on the social ills of the time that drove discovery including infectious diseases (Griffiths, Hershey-Chase, Koch's Postulates), and attention is given to less-known figures such as Meischer, Franklin, and Wallace.

The History of Cell Biology, Embryology and Genetics

Sources that trace the history of cell biology, developmental biology, and genetics often juxtapose excerpts from original historical texts with critical analysis, summarize history through the use of timelines, or reconstruct history through biographies, oral history projects, and interviews. The "Discovery of the Cell" (DoTC) project reflects contributions from historians of science and includes excerpts from historical texts, giving special attention to "the significance and conceptual value of a particular discovery" using a color coding scheme throughout the website that goes back as far as the 1500s (Table 3). GarlandScience has published a DVD titled "Exploring the Living Cell," which contains a historical section that uses drawings and text to illustrate the work of early cell biologists (Table 3). Another interesting project, "The Embryo Project Encyclopedia," is searchable by place, person, or object, and provides results in the form of a map that depicts the historical and relational links of these objects (Arizona State University, Table 3). *Whose View of Life* contains a rich and detailed history of early stem cell biology that serves as a foundation for current day stem cell research (Maienschein, Table 3). UC Berkeley has created an oral histories project around the same topic, using Proposition 71 in California as a case study to document the relationship between science and society through interviews with stem cell biologists and policy makers (Table 3). Though the Berkeley project does not use historical texts, its construction illustrates the need to preserve history in the making—something also observed in interviews from the "Program in Bioscience and Biotechnology Studies," which capture the experiences, passions, and relationships of biologists who were poised to take biotechnology in a new direction. Similar shifts in biological research are reflected upon in "Language and Science," which is the first of three chapters in *Refiguring Life* (Table 3). Here, Keller traces the emergence of genetics as a new field of biology and suggests that through its associated language, genetics led to the marginalization of the long-standing field of embryology. This kind of tracing back reminds students that as biologists continue to make discoveries, new fields will develop and old ideas may fade only to re-emerge in a new context. For example, some Larmarckian forms of inheritance are recognized today as the consequence of epigenetic programming events, which can be responsive to the environment (Jablonka *et al.*, 1998).

A Word of Caution in Using the History of Biology to Teach Discovery

A paper titled "How *Not* to Teach History of Science," cautions educators from using history as a tool to view science as "triumphant discovery" or "pathological error" (Allchin, 2000). To suggest that some scientists in the past are "losers" rather than contributors to a larger field of study results in three negative outcomes: It suggests that there is a "right answer," that any results that don't move the investigator closer to this predicted and defined answer are useless, and that biology is static. One of the most famous "losers" depicted in biology textbooks is Jean-Baptiste Lamarck. A biased representation of Lamarck is strengthened when he is pitted against Charles Darwin. However, Lamarck and Darwin did not see their theories of evolution as mutually exclusive, and more recently Lamarck's work has been resurrected by a better understanding of how

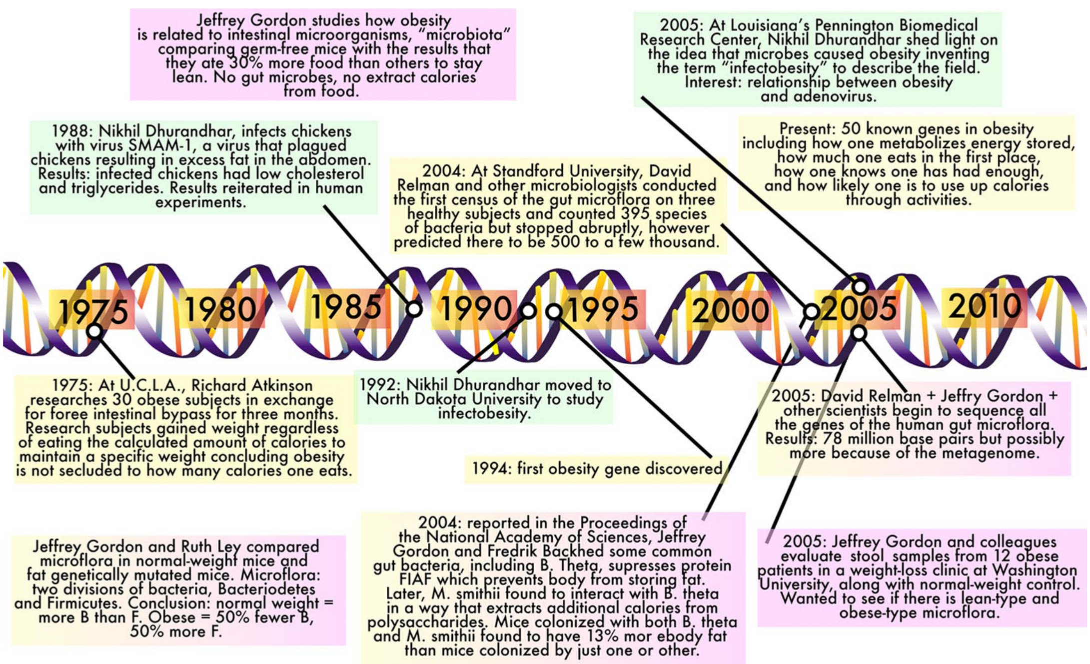

Figure 2. Example of student-constructed metagenomics and obesity timeline. When asked to submit a written summary of readings, which included research and review articles, this student spontaneously provided an additional timeline. This submission came midway through an intermediate-level course on the Human Genome Project and illustrates multiple approaches and methods to understanding the genetic and environmental contributions to the contemporary interdisciplinary problem of obesity.

environmental factors can impact epigenetic modification of the genome. By using these theories together rather than in opposition, instructors can emphasize the importance of context in determining *when,* and how, these theories explain various biological phenomena. A multiplicity of approaches in addressing the same problem is useful because it gives students permission to be more courageous in putting forth new ideas.

One will also want to refrain from teaching "cookbook history," presenting biological research or discoveries outside of their historical contexts (Allchin, 2000). When students read "historical" texts, they might criticize the experimental approach of a biologist, but use present day knowledge to do so. To help students place themselves back in time, one can use an excellent set of historical biographies in *Microbe Hunters*, originally published in 1928 (Table 3). The author uses language that was appropriate for the time, and though he may embellish here and there, he captures the personalities as well as the political and national alliances of various cell biologists (Summers, 1998). One important characteristic of these narratives is that they are not shy about highlighting the "pathological error" associated with a need to be "right," and the frustrations that accompany experimentation that did not go as planned (see Koch and Metchnikoff chapters). When asking students to reflect on how these historical figures could have improved their experimental models, they must be reminded to stay true to the technologies and knowledge available at that point in time. These stories can be further contextualized using other articles that delve deeper into the social context. In the case of Louis Pasteur and Robert Koch, case studies show how the politics of war ignited animosity between individuals and competing schools of thought with respect to public health practices (Ullmann, 2007). Collectively these perspectives illustrate that technology is an important tool, and can be a driver or limiting factor in biological discovery.

Lastly, we recommend moving away from using history to showcase biological discoveries as products of serendipity, as it may convince students that biology is not about good experimentation but rather dumb luck. If we make a conscious effort to demonstrate that knowledge is built over time by multiple researchers who take years to acquire their expertise, students may be less inclined to rush toward finding the answers to problems, and spend time on meaningful observations and analysis. Timelines that display the contributions of multiple disciplines to one major discovery, such as DNA being the molecule of heredity, illustrate the power of integration and the vast amount of expertise needed to arrive at this finding (Figure 1, class-constructed timeline; Figure 2, student-constructed timeline). Historical sources and timelines highlight one of the most influential factors of biological discovery, which is not serendipity, but sagacity—the ability through experience to distinguish meaningful deviations from experimental noise or human error (Gest, 1997).

WHAT INTEGRATION CAN LOOK LIKE

The integration of social context into biology courses does not revolve around a single pedagogy or a specified amount of time. To highlight the applications of biology in society, a TV commercial advertising a vaccine, drug, or product can be used to open a lecture based on the biological principles that led to the development of the product. Asking students whether they would use the product stimulates their ability to apply knowledge learned in the classroom to decisions outside of class. Approaches that require more instructor preparation or student work outside of class might be more suitable for smaller classes. A number of journals have compiled short features and biographies of scientists. Coordinating these articles with textbook chapters that review the work of these scientists can reveal the personal side of science as well as the discovery process (Table 1). More expansive projects can center on problem-based learning modules or case studies in science (Allen and Tanner, 2003; Herreid, 2007; Table 2). These approaches often center on a narrative that describes human characters navigating real world experiences. Case studies constructed from the biographies of scientists driven by curiosity, ambition, and/or a need to restore social justice allow instructors to act as liaisons between classroom material and real-world context (Chamany, 2001, 2006). Case-study teaching can be combined with more traditional problem-solving activities, expanded as overarching themes for courses, and tailored to highlight local or institutional relevance. Some instructors have charged students to develop case studies that connect course material to the history, people, or social issues surrounding a biological topic. This approach not only reveals what students find relevant, but the student products can contribute to a repository for future courses, lessening the load on the instructor.

The Cell Biology for Life (CBL) project (referenced in Table 2) has been developed in an effort to share educational resources that integrate the people, history, and social issues of biology with appropriate assessments and evaluation, and is described here as an example of what this approach can look like in practice. CBL is a collection of modules centered on case-based teaching and learning that uses three contemporary topics to teach basic cell biology concepts and methods. Each module focuses on an area of biological research with multiple avenues of social relevance: botulinum toxin and secretion, stem cell research and cell signaling, and the human papillomavirus (HPV) and its association with oncogenesis. Together, the CBL modules cover more than half of the material in a standard cell biology course. Used in succession, they move from basic cell biology to more sophisticated cell biology. Students learn about cell structures, cell division, and cell differentiation in the stem cell module, and are introduced to prokaryotic cells and specialized cell processes such as neurotransmission and muscle contraction in the botulinum toxin module. Students also investigate the role that genetics and viruses play in cell pathology in the HPV module. These fundamental biological principles and methods are placed in social contexts: stem cell research and its use in screening drugs and toxins, and the ethical dilemmas surrounding oocyte donation and embryo termination; botulinum toxin and its application in medicine, esthetics, and biowarfare; and HPV diagnostics, vaccines, and cervical cancer treatments that infringe on indigenous knowledge.

To help instructors teach this contextual material and assess student learning, each CBL module contains a primer that reviews the history, science, and social issues of the topic. The primers contain a set of multimedia and literature resources organized by subject, teaching notes that point to relevant book chapters from texts published by Garland Science, assignments and assessments that promote active student learning through primary literature, and a set of password-protected answer keys. By joining the elements of CBL with traditional methods of teaching, instructors can provide students with the opportunity to see the social implications of conducting biological research, and to develop the skills necessary to become contributive members of society.

RELEVANCE AND APPROPRIATE ASSESSMENT

Researchers in educational psychology are careful to note that because learning is a developmental process, presentation of interdisciplinary content or complex real-world problems needs careful consideration, and this extends to assessment of student learning outcomes. In this regard, educators should be mindful of the specific outcomes they hope to achieve through interdisciplinary learning. Hierarchical scaffolding, such as Bloom's Taxonomy, allows instructors to match resources and assignments to specific types of learning, while performance assessments more directly measure a student's ability to evaluate and choose among diverse perspectives or methodological approaches to solve a problem (Forehand, 2005; Shavelson, *et al*., 1991).

Assessment of integrative learning can take on many forms, some of which may seem unfamiliar to both instructors and students. The use of analytical rubrics will greatly improve clear communication of learning outcomes and goals and are often used for performance assessments that mimic professional activities, such as grant writing, panel participation, and peer review (Allen and Tanner, 2006). These assignments gauge biological content knowledge, application of knowledge, and the impact of that knowledge on society. A method that has been adopted by some biology educators requires students to use and translate their content knowledge to actions aimed at influencing social policy. An example of this is the sending of letters to legislators or written statements that serve as platforms for a mock community forum (Ebert-May *et al.*, 1997; Chamany, Table 2). One educator asked students to submit term papers on various perspectives of stem cell research that eventually shaped a compendium reader for a traditional developmental biology textbook (Gilbert *et al.,* 2005; Table 2).

In large-sized classes, where exams are used to evaluate student learning, social context and history can be integrated with more traditional lines of questioning. For example, an exam on the principles of evolution can ask students to address the contributions or challenges from other disciplines to the theory of evolution. By asking students to recall the individuals and theories that challenge Charles Darwin and Alfred Wallace's proposed mechanisms of evolution, they are reminded that biological knowledge is constructed by people, and that theories and proposed mechanisms continue to shift over time.

A rigorous exam question can inspire student learning, especially if students have not seen the context in class before. An example of this type of question is shown in Box 1, which assesses student knowledge about basic principles of the central dogma using the socially relevant topic of HPV diagnostics, visual screening practices, vaccination, and treatment. This question could easily be transformed into a series of multiple-choice questions that evaluate the student's ability to synthesize knowledge.

Box 1. Example of Final Exam Question in Cell Biology Course

Recently, cervical cancer screening has been approached via an HPV diagnostic that detects the presence of HPV (Digene Hybrid Capture test). We also know that some types of HPV promote cancer more than others because they carry different variants of the E6 and E7 protein (for instance HPV 16 carries genetic variants that code for E6 and E7 that bind tightly to the host proteins that normally regulate cancer development). Some would argue that screening women for high-risk HPV DNA is not helpful, as it will not definitively distinguish who is at risk for cancer. On May 10, 2005, Molden *et al.* published a paper announcing the use of a "PreTect HPV-Proofer" diagnostic test that detects mRNA rather than DNA.

a. Before DNA technology was available, how did we screen for cervical cancer, and what are the pros and cons of this screening practice?
b. What does the HPV Digene Test detect and how does it work?
c. How does the Pretect HPV Proofer test alleviate some of the problems associated with the Digene test in terms of presenting young women with murky or confusing health status information regarding cancer risk when infected with a high-risk strain of HPV?
d. How does genetic diversity in humans and in viruses lead to different cervical cancer outcomes in women exposed to HPV?
e. How does the environment play a role in cancer development?
f. Why are women in the developing world so much more susceptible to cervical cancer and will the current vaccines correct this inequity?
g. How might you deliver a "kill yourself" gene to precancerous cells in the cervix? Be clear on how you would target these cells specifically and how you would deliver the gene to the cells.

In this question, no memorization of specific proteins or technologies is required as the detailed information is provided. Rather, students were asked to evaluate and select the best approach in different situations. Students had been exposed to three modules from CBL (Table 2) and were asked to focus on concepts instead of details. The question evaluates a student's ability to apply concepts related to genetic diversity (b and d), gene expression (c), and gene–environment interactions (e). The question also addresses history and application of biological knowledge to society (a) in a global context (f). This latter subquestion also asks students to consider indigenous low-cost and low-tech approaches that might be more suitable for countries with limited resources, including visual inspection acetic acid analysis and cervical cancer treatment with curcumin (active ingredient of tumeric). The last subquestion (g) asks students to integrate knowledge from previous modules that focused on signal transduction, cell surface markers, and gene therapy techniques using chimeric proteins.

Integrating the social context and the history of biology in assessment and evaluation of student learning demonstrates that these perspectives are integral to biology learning and not simply entertaining asides for class sessions. This approach also suggests that we expect students to be able to continue making these connections, and that this is an essential skill for all members of society, be they biology researchers, policy makers, or other influential citizens of their local, national, and international communities.

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