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CURRICULUM ARTICLE

"Virtual Inquiry": Teaching Molecular Aspects of Evolutionary Biology Through Computer-Based Inquiry

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Abstract Genetic diversity is a core concept in evolutionary biology; genetic variation is a prerequisite for heritable differential selection, and biodiversity plays a central role in debates about environmental policy today. The technique of gel electrophoresis provides a simple, visual demonstration of the variation that exists on the genetic level among individuals of a species. "DNA fingerprinting", in particular, is a method that exploits variation within species and has been explored extensively by the news media and popular television shows. In this paper, we suggest that science educators can capitalize on this momentum of interest and incorporate gel electrophoresis to their teaching as a starting point for the examination of genetic diversity that connects fundamental concepts of the molecular, cellular, organismic, and population levels of ecological organization. As a pedagogical tool toward this aim, we examine how increasingly complex inquiry learning can be supported in classrooms by the application of software tools called "virtual laboratories". The paper is a synthesis of current research on the integration of software design and instructional design to illustrate how two software tools can be employed for different levels of inquiry learning.

Keywords Genetic diversity · Virtual laboratories · Inquiry learning · Learning and instruction

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Genetic diversity is frequently misunderstood or underestimated in its importance—perhaps due to the disconnected coverage of related concepts in current curricula. For example, despite the establishment of "evolution and equilibrium" as a unifying theme in national standards (NSES 1995), the molecular account of biological function is not well integrated with curricular treatments of evolution in commonly used textbooks (e.g., Raven et al. 2005; Lawson 2006). This lack of alignment between standards and key milestones for measured understanding has been documented before (Li et al. 2006) and is echoed by this manuscript with focus on genetic variation and diversity. Further exacerbating the problem, teachers either do not have enough time to cover these concepts or simply choose

to present them superficially (Aleixandre 1994; Rutledge and Mitchell 2002). This is especially the case if teachers are not confident in their own content knowledge or fear repercussions from students and parents (Griffith and Brem 2004). Fueled partly by this disproportional coverage, misconceptions about genetic variations are common (Gould 1988; Shtulman 2005; Gelman 2003; Sinatra et al. 2007). Given that students are facing a future that will be very different if our current practices continue to reduce biodiversity, understanding the molecular bases of evolutionary change can help students comprehend the larger concept and its implications for their personal future (Husman and Lens 1999).

Curriculum structure, teacher confidence, and controversies surrounding the teaching of evolution may all help to fuel misconceptions about genetic variations (Gould 1988; Shtulman 2005; Gelman 2003; Sinatra et al. 2007). If we can help students to understand genetic variation and its role in evolution, we may be able not only to help them overcome their misconceptions but also prepare them to be better stewards of the planet and advocates for their own future. Certainly, genetic diversity can be presented in a number of different ways. We, however, believe that gel electrophoresis has particular promise, for two reasons. First, reference to gel electrophoresis frequently arises in popular culture, through television shows about crime scene investigations. It is a technique that students are likely to associate with "high-tech" professions made popular by these television shows. Second, gel electrophoresis provides concrete, visible evidence for genetic variation that exist between members of a species. Accordingly, we first provide a brief overview of the gel electrophoresis process, then briefly review prior research on how teachers can establish increasingly complex inquiry depending on their student' experiences and developmental levels. Finally, we will illustrate how two common software tools in the domain of gel electrophoresis can be used for different levels of inquiry learning. For the comparison of these tools, we present a framework that teachers can adopt and adapt in selecting virtual laboratories (VRLs).

A Brief Introduction to Genetic Variation and Gel Electrophoresis

DNA-based technologies are now used in many aspects of scientific and medical practice, including paternity testing, forensic identification and crime-scene analysis, genetic counseling, and medical diagnostics. Genetics has also become the stuff of primetime television and high-tech thrillers, thanks to the ability of screenwriters to produce exciting, plausible sounding dialogue while actors hover over mysterious equipment and plot lines that turn on the results of these almost magical tests. In reality, understanding how a person's genetic blueprint is read is not very difficult, and the techniques and conversations that enthrall audiences can be simulated in a high school or college classroom (though, sadly, without the $300 haircuts and expert mood lighting). The use of genetics in the forensic science, healthcare, and evolutionary biology laboratories rests on the fact that populations possess genetic variation that is the result of evolution and inheritance. This variation creates a unique profile for each individual that can reveal identity, health condition as well as ancestry (Novick and Catley 2007). At each organizational levels—cellular, organismic, familiar, and phylogenetic—the key is identifying sequences or repeats in coding or noncoding DNA that are statistically unlikely to reoccur except through inheritance.

Noncoding DNA is particularly useful in identifying individuals and a person's lineage because mutations within noncoding DNA are rarely deleterious. Thus, there is a high degree of variation in noncoding DNA that is not subjected to selection pressures. In any individual and in their population, there exist a large number of these known noncoding DNA sites. The presence and length of these segments at different sites on the DNA strand are specific to individuals and groups. With innovative biotechnology tools, such as gel electrophoresis, the length and composition of these polymorphic DNA sections can now be documented. That is, the teaching of heredity, developmental biology, and evolution can be integrated in the context of biotechnology applications starting with the concrete demonstration and examination of factors of genetic variation within individuals of a species and even diversity between species. The purpose of this manuscript is to illustrate how teachers can start planning toward developing such integrated teaching using gel electrophoresis.

Using Gel Electrophoresis to Illustrate Genetic Variation

The idea behind gel electrophoresis is that larger DNA molecules move a shorter distance than smaller ones when they are pushed along by an electric current in a porous medium such as an agarose gel (a substance that is similar to gelatin and Jell-O). DNA is negatively charged because of its sugar-phosphate backbone. Therefore, when a current is passed through the gel, the DNA fragments travel in a straight line toward the positive end of the gel and away from the negative end. Smaller fragments will move to a further distance than larger ones because of the sieve effect of the gel, spreading the DNA fragments out by size, over the length of the gel. The agarose gel is prepared with slots on one end that are called "wells" for loading DNA samples (Fig. 1). The DNA sample of unknown composition is loaded in some of the wells, while another sample with

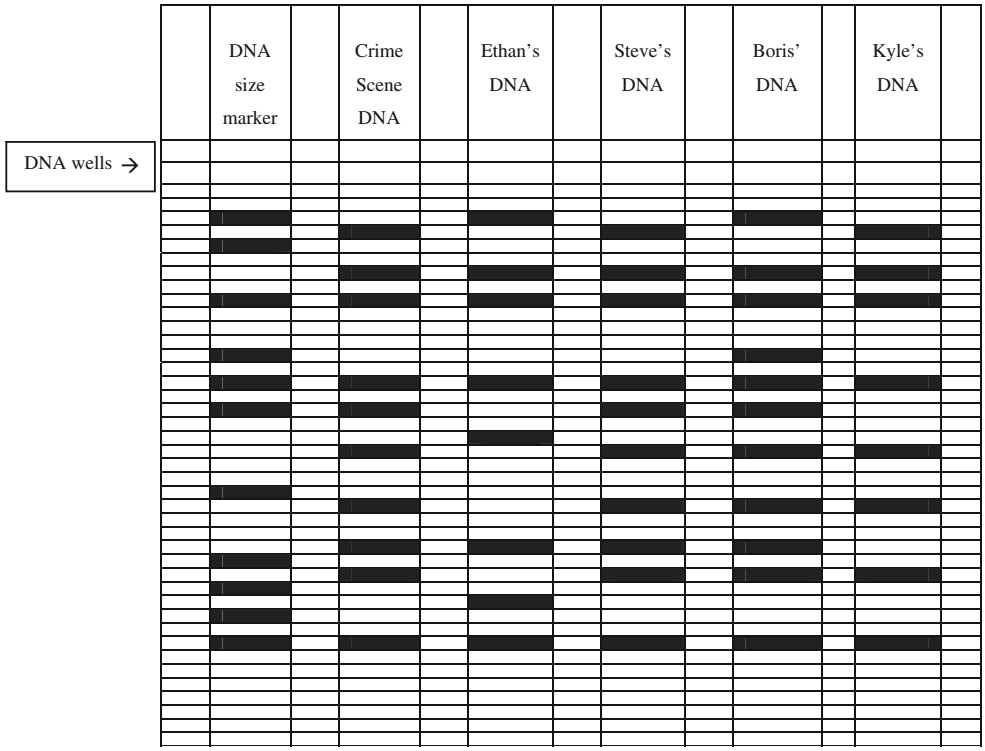

Fig. 1 The results of DNA fingerprinting performed to match DNA from a crime scene to four potential suspects

known-size DNA fragments is loaded to serve as a molecular ruler. This molecular ruler (or DNA ruler) allows the measurement of fragment length in the unknown samples. In the scientific laboratory, the gel contains a DNA-specific fluorescent dye, such as ethidium bromide, to visualize the results. The visual inspection of the DNA electrophoresis results allows us to determine which variants (shorter or longer DNA fragments) are present in an individual. To establish statistical significance, each DNA-based identification (or DNA fingerprint) uses DNA fragments from several marker sites. Since the frequency of markers in a population can be ascertained and the presence of each marker in an individual is independent from the existence of another marker, the combined occurrence of several markers is unique to an individual. With this method, when large numbers of independent markers are observed, the statistical probability of having two identical fingerprints within the current human population on Earth is close to zero[1] making fingerprinting an excellent mode of identification (Fig. 1).

However, successfully employing the gel electrophoresis method requires skill, time, and safety precautions associated with hands-on activities. Furthermore, many of the currently available fingerprinting classroom kits focus students on replicating a complex procedure rather than understanding the concepts that the lab is meant to demonstrate. For these reasons, a traditional, hands-on "wet lab" poses challenges for classroom gel electrophoresis into the classroom. Fortunately, with advances in technology, computer-based "virtual laboratories" lessen the preparatory burden of hands on laboratories and allow instructors to focus on inquiry-based learning rather than safety and technique. VRLs reportedly are effective in substituting for the wet lab (Klahr et al. 2007) and, depending on their design features (Toth 2009a; Quintana et al. 2004; Ainsworth 2008), have potential to significantly contribute to the cognitive, social, and affective elements of inquiry learning (Toth 2009b). As a result, there is increased interest among university professors and classroom teachers in designing fully virtual or blended inquiry learning environments (Toth et al. 2008). The next section examines the characteristics of popular virtual laboratories and analyzes their potential to support inquiry learning.

Virtual Laboratories to Teach Genetic Variation

VRLs are software tools that allow users to conduct scientific inquiry in a way that captures many of the conceptual features of a hands-on laboratory. A quick search of available gel electrophoresis teaching tools returns static images of data outcome, noninteractive demonstrations, and minimally interactive simulations of the process and very few tools that provide opportunity for the examination of the complex, dynamic processes. Of the few tools available for interactive, inquiry learning in this domain, the authors have extensively used three tools. One

[1] The only exception is the case of genetically identical twins, whose DNA is largely the same.

is a component of the Public Broadcasting System (PBS 2008) "on a killer's trail" investigation, another tool is available from the gel electrophoresis laboratory from the Genetic Science Learning Center (GSLC) at the University of Utah (GSCL 2008). The third software tool we have used in our classrooms and in our teacher education programs is the MyDNA unit of the Molecules in Motion project at the University of Massachusetts (MyDNA 2003). Since the PBS (2008) and GSLC tools have similar characteristics, this paper focuses only on the description of two tools, to compare and contrast the potential of these virtual laboratories for classroom inquiry learning.

The GSLC gel electrophoresis laboratory This software tool simulates the essential procedures of the gel electrophoresis protocol, including making electrophoresis gels from scratch, loading DNA samples into wells on the gel, and setting up the apparatus to separate DNA fragments by size under electric current (Fig. 2). The resulting DNA fragment distribution is then displayed along a DNA ladder. This ladder or "DNA ruler" is a sample with known-length DNA fragments that helps us approximate the length of each fragment in our experimental sample (Fig. 3). However, this tool does not provide an opportunity for learning by designing experiments and analyzing resulting data.

The MyDNA virtual laboratory Another gel electrophoresis VRL is the MyDNA module (Fig. 4). This tool allows the exploration of user selected variables (for example, gel concentration and voltage) as they relate to the gel electrophoresis outcome. Three possible levels of concentration and nine levels of voltage can be used, and each setting will result in the scientifically accurate movement of DNA fragments. In this way, students can investigate various research questions about the role of these independent variables on the outcome of the gel electrophoresis process. They can reason about the mechanisms that explain the outcome data.

Based on these unique characteristics of each tool, educators are tasked to create an effective inquiry environment that is appropriate for their own goals for their students' learning. These considerations of instructional design with software tool application require considerable expertise (Toth 2009a; Quintana et al. 2004). To aid the development of such expertise, we provide a practice-focused summary of prior research on inquiry learning and illustrate how the two tools above can be employed at different levels of inquiry.

Levels of Inquiry

Inquiry is defined as the coordination of asking questions, using evidence to respond to these questions, formulating explanations based on empirical evidence, and communicating explanations and justifications for domain understanding (NRC 2000). Arguably, inquiry education has earned a poor reputation in many circles. Early attempts to provide students with authentic, open-ended opportunities for exploration frequently resulted in students meandering through projects, hopelessly lost, and potentially constructing more misconceptions than scientifically correct knowledge. Educators were, in turn, frustrated and overburdened, trying to help each student follow their unique circuitous

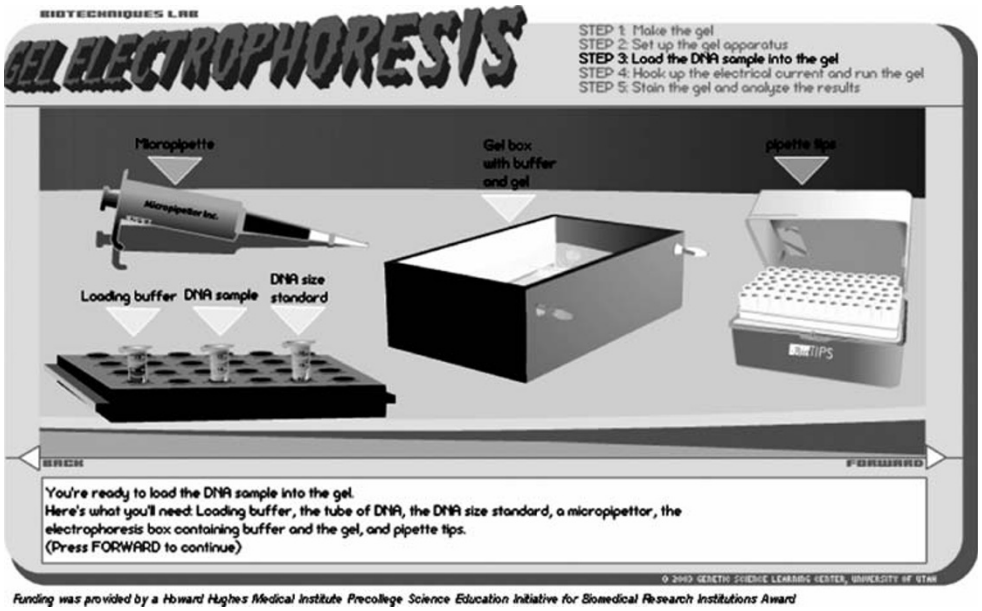

Fig. 2 The gel electrophoresis virtual laboratory available at http://learn.genetics.utal.edu. Copyright: Genetic Science Learning Center

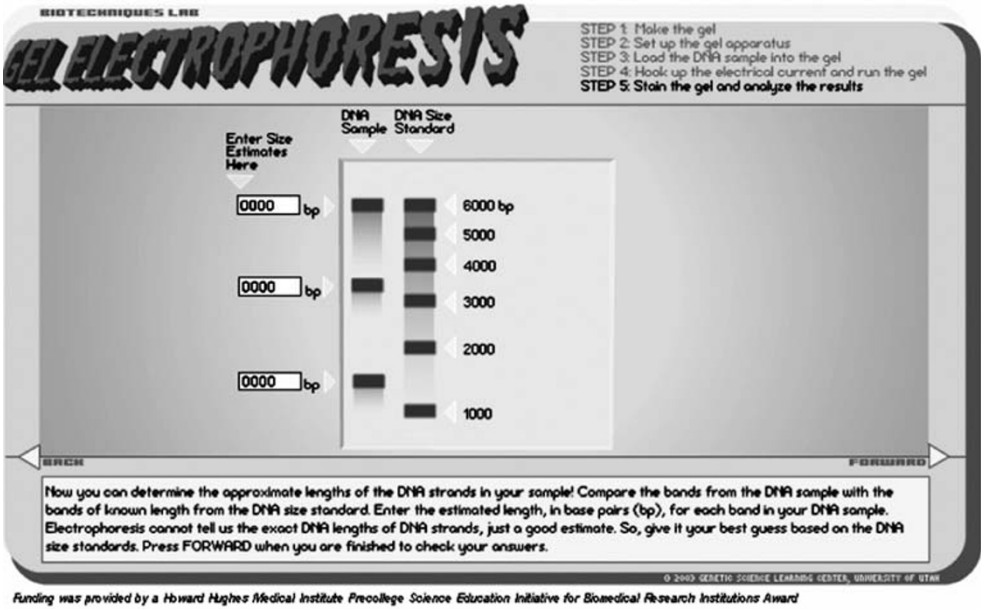

Fig. 3 Data evaluation with the GSLC software tool

route to understanding. True inquiry learning is not stumbling in the dark, but a set of carefully engineered opportunities to explore (Abrams 2004; Coburn 2000). Clearly planned inquiry instruction has been effective in large-scale studies (Blanchard et al. 2007).

Recent perspective of structuring inquiry illustrates that as students gain knowledge and confidence in inquiry, the constraints of inquiry supports can be relaxed for increased independence by students (Rezba et al. 1999; Bell et al. 2005). This approach proposes that inquiry can be

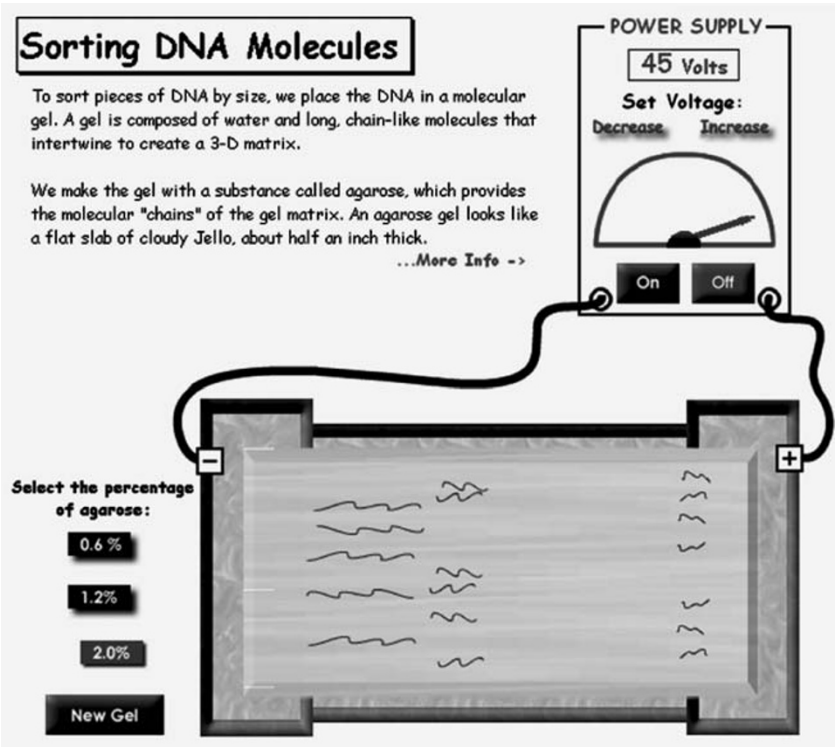

Fig. 4 The MyDNA "sorting DNA molecules" module available from the University of Massachusetts at http://www.biochem.umass.edu/mydna/modules/sort.html. Credit: This virtual laboratory module was created by "Molecules in Motion". Permission to use for education and research publication is granted by the project development team to the author. The MyDNA project is sponsored by a grant from the Camille Henry Dreyfus Foundation, Inc.

conducted at different levels of sophistication depending on students' developmental stages and prior experiences. Teachers can tailor the complexity of students' inquiry by explicitly predetermining one or more component steps, while allowing students to independently make related decisions. For practical purposes, this manuscript considers three phases of inquiry learning modeled on prior research in the cognitive literature (Fay and Klahr 1996). These phases are *searching* the task environment by way of experimental design, *evaluating* data results and *formulating inferences* to reason for the mechanisms and processes that brought about the patterns in outcome data. Each of these phases includes several component steps that can be subject to a decision on teacher control or independent student investigation. For example, related to the phase of searching the task environment, the pivotal decision that teachers may make or leave to students is that of developing a research questions that drives investigation (Wallace et al. 1998). In combination with available materials and resources, this question will influence students' design of empirical tests, their following preset protocols for generating evidence, or collecting existing data. As part of the second evaluation phase of inquiry, decisions of independence can focus on methods to measure data outcome, determining data analysis and interpreting variable effects. The subsequent reasoning phase of inquiry includes decisions about inferring the mechanisms of variable effects, communicating results, and generating new goals for continued learning investigations.

Based on the above conceptual framework, a level 1 inquiry (Rezba et al. 1999), also called confirmatory inquiry (Bell et al. 2005), means that students follow mainly predetermined steps for the search, evaluation, and reasoning phases albeit with focus on finding solutions for a specific driving question that their teacher determines. For example, in our domain, students may receive the driving question from teachers on whether increase in gel concentration contributes to the distance DNA fragments travel. This driving question focuses students' inquiry on confirmation of prior (though to them unknown) results. They can use ready-made data to evaluate the relationship between gel concentration and DNA fragment distance. With confirmatory inquiry, students reasoning and conclusions simply corroborate a prior scientific statement about the role of gel concentration (Table 1).

Conducting level 2 (Rezba et al. 1999) or structured inquiry (Bell et al. 2005; Coburn 2000) means that students receive slightly less support in the form of prestated research questions or investigation methods. For example, the driving question may lead students to investigate several variables to influence the electrophoresis outcome. Students determine *either* the method of data collection (search), the method of data analysis (evaluation), or the way to provide an explanation (reason) to the guiding question and continue to follow highly structured steps for the other processes of inquiry (Table 1).

Similarly, a level 3 guided inquiry implies a higher level of student independence with fewer predetermined steps. Finally, level 4 or open inquiry implies that all essential elements of investigation (including all steps of search, evaluation, and reasoning) are decided independently by students (Table 1). Despite significant prior research, the potential of inquiry learning currently available textbooks have been documented to employ level 1 or level 2 inquiry activities, commonly referred to as "cookbook" laboratories (Bell et al. 2005). However, software tools are available to assist teachers move beyond traditional laboratories and implement more advanced levels of inquiry learning in their classrooms.

Supporting Different Levels of Inquiry Learning

Table 2 examines the two software tools introduced above for their potential to support inquiry learning. Our aim with this specific comparison is to provide example activities

Table 1 Possible student activities under different levels of inquiry in the domain of gel electrophoresis

Level	Description of student activities under different levels of inquiry
1	Confirmatory inquiry: What is the role of gel concentration in the distance DNA fragments travel? Using a preselected virtual laboratory and by precisely following a predeveloped data analysis method, students verify the influence of gel concentration on the distance DNA fragment travel
2	Structured inquiry: What is the role of gel concentration in the distance DNA fragments travel? Using a predetermined virtual laboratory students determines either the method of data collection (search), the method of data analysis (evaluation), or the way to provide an explanation (reason) to the guiding question. The conduct of other phases is controlled by the teacher
3	Guided inquiry: What variables of gel electrophoresis influence the distance DNA fragments travel? Using a predetermined virtual laboratory students determine more than one: the method of data collection (search), the method of data analysis (evaluation), the way to provide an explanation (reason) to the guiding question. The conduct of other phases is controlled by the teacher
4	Open inquiry: Students formulate a driving question about a variable they wish to investigate and collect data about the effects of these variables by designing experimental tests. They independently determine the materials, methods of data collection, and data analysis and communicate their research results

Table 2 Comparison of students' activities with the two different environments as relevant to the three phases of inquiry

Inquiry phases and steps	Inquiry supports	
	With the GSLC VRL	With the MyDNA VRL
Search phase		
Ask research questions	None predetermined but confirmatory question to focus on process can be added	User determined questions can focus on the effects of voltage or concentration
Select variables	No variable selection possible	User determined selection of variables via point and click
Design experiments	No experimentation via designing tests is possible	Experimental design to investigate different variables. Click of button automation eases cognitive load
Evaluation phase		
Determine data analysis methods	Measurement method given—compare predetermined end-product (fragment distribution) to molecular ruler	User chooses method of measurement
Measure data outcome/ examine properties of data	User determines length of each fragment based on molecular ruler (ladder DNA)	User chooses to examine either distance traveled or end-product distribution—based on method selected above
Interpret variable effects on data outcome	No variable effect can be documented	Evaluate the effect (or lack of effect) of user-selected variables based on data
Reasoning phase		
Infer the mechanism of the effects of focal variables	Predetermined data provides visual support to conceptualize the fragment travel	Effect of user-selected variables is determined based on data outcome by users
Nature of reasoning	Practical reasoning focuses on "proof-of-concept" or confirmation	Scientific reasoning about variable effects on user selected dependent variable
Inform new goals for learning	Continued reasoning is possible about mechanisms of fragment distribution	Continued reasoning is possible about mechanisms of fragment distribution or distance traveled

that are appropriate for the instructional goal of learning genetic variation, as a starting point for the understanding of evolutionary change and diversity across species. With appropriate decisions in the search, evaluation, and reasoning phases of inquiry, these software tools can be employed for different levels of classroom inquiry learning.

As illustrated in Table 2, by design, the *search phase* of inquiry learning is highly constrained in the GLSC VRL. Since there are no variables to be modified, experimentation is not possible with this tool. With a teacher-developed guiding question, however, this simple software tool can be turned into an excellent first step toward independent inquiry in the domain of gel electrophoresis. In comparison to the GSLC tool, the MyDNA VRL supports a higher level of independence and user interaction as it allows for the formulation of a research question about the role of variables that can be manipulated such as concentration and voltage. Students can select from a variety of possible settings for these variables via the click of a button and design unlimited experimental tests to search for data that illustrate the effect of the selected variables on the gel electrophoresis outcome.

Similarly, the supports for the *evaluation phase* of inquiry learning are quite different in the two tools. The GSLC VRL provides a predetermined measurement method to ascertain the size of unknown DNA fragments based on the known lengths of fragments in the DNA ladder (or "DNA ruler"). However, the MyDNA (2003) software tool omits the measurement of DNA fragment lengths with a DNA ladder; thus, users are not restricted to simply interpreting the resulting DNA fingerprint pattern but can individually determine what they will measure. For example, they can measure either the relative distribution of small-, large-, and medium-sized fragments or the length of the travel by each fragment in response to changes in the variables of concentration and voltage (Table 1). Accordingly, the MyDNA tool allows for the scientific examination of variable contribution while simplifying the traditional protocol to ease inquiry learning. This particular difference in the two tools illustrates why it is interesting (and perhaps necessary) to use both tools at different stages of inquiry learning in this domain.

To support activities in the *reasoning phase* of scientific inquiry, both tools are effective in generating continued

reasoning about the mechanism of fragment distribution and the genetic variability this distribution means for a population. However, the reasoning inherent in the GSLC tool focuses on the practical problem of determining the outcome distribution of DNA fragments in general. Conversely, the MyDNA tool supports scientific reasoning based on the empirical data available from tests performed with different variable settings. This added detail opens the learning process to more complex thinking and inferences about the mechanisms that brought about the outcome data. One such mechanism that students may discover by way of experimental design and inquiry learning is that changes in gel pore size correspond to change in gel concentration. This change in pore size explains why a gel with higher concentration results in shorter distance traveled by different-size DNA fragments.

In summary, the two software tools introduced here allow teachers to consider ways to implement different levels of inquiry learning in their classrooms. The GSLC VRL is most appropriate for confirmatory inquiry employed by a less experienced audience, or as an introduction to the conceptual basis of gel electrophoresis with the aim to motivate further inquiry about specific interactions between variables. The MyDNA tool extends the possibilities of inquiry learning as it allows teachers to implement guided inquiry with more freedom for students to design experimental tests, examine data results, and determine the mechanisms of variable effects to answer a driving question they developed about these variables. Both of these tools can motivate follow-up investigations by way of hands-on laboratories thus leading teachers to the development of blended inquiry environments (Toth et al. 2008). Jointly, the inquiry activities possible with these tools can provide motivation and conceptual grounding for the continued examination of genetic diversity as a mechanism of evolutionary change.

Conclusion and Implication for Further Research

The concept of genetic diversity is not only central to understanding evolution but also quite challenging to learn. Employing gel electrophoresis in the classroom provides students with tools for visualizing the concept of genetic variability among individuals of a species and taps into their interest in forensic tools that had been generated by popular media. As cognitive scientists, science education researchers, biologists, and geneticists, our goal with this article was not to provide a specific curriculum but to provide teachers the research-based grounding for their own decisions during instructional design for their specific students. With this aim, the paper illustrated the potential of two virtual laboratories to introduce students to gel electrophoresis in a safe, low-overhead environment. These tools also allow educators to design inquiry projects that effectively move students through a trajectory of increasing expertise in inquiry and the learning of genetic diversity, as a fundamental aspect of evolutionary processes. However, with constraint on space, this paper does not fully document the variety of methods to teach concepts of evolutionary biology especially in the light of the many available genetic databases that allow for the further examination of data results, beyond the initial visual illustration of these existing genetic differences. Teaching these additional molecular aspects of evolutionary biology is of continued research interest.

References

Abrams E. Talking and doing science: important elements in a teaching-for-understanding approach. In: Mintzes JJ, Vandersee JH, Novak JD, editors. Teaching science for understanding: a human constructivist view. San Diego: Academic; 2004. p. 307–21.

Ainsworth S. How do animations influence learning? In: Robinson D, Schraw G, editors. Current perspectives on cognition, learning and instruction: recent innovations in educational technology that facilitate student learning. Chapter 3. Charlotte: Information Age; 2008. p. 37–67.

Aleixandre MPJ. Teaching evolution and natural selection: a look at textbooks and teachers. J Res Sci Teach. 1994;31:519–35.

Bell R, Smetana L, Binns I. Simplifying inquiry instruction. Sci Teach. 2005;72(7):30–3.

Blanchard M, Southerland S, Annetta L. Investigating the effectiveness of inquiry-based versus traditional teaching methods in middle and high school laboratory settings. Proceedings of the 2007 NARST conference, New Orleans, LA; 2007.

Coburn A. An inquiry primer. Science Scope. 2000; 42–44.

Fay AL, Klahr D. Knowing about guessing and guessing about knowing: preschoolers' understanding of indeterminacy. Child Dev. 1996;67:689–716.

Gelman SA. The essential child: origins of essentialism in everyday thought. Oxford: Oxford University Press; 2003.

Genetic Science Learning Center (2008). http://learn.genetics.utah.edu Retrieved 7/18/08

Gould SJ. Trends and changes in variance: a new slant on progress and directionality in evolution. J Paleontol. 1988;62:319–29.

Griffith JA, Brem SK. Teaching evolutionary biology: pressures, stress, and coping. J Res Sci Teach. 2004;41(8):791–809.

Husman J, Lens W. The role of the future in student motivation. Educ Psychol. 1999;34:113–25.

Klahr D, Triona LM, Williams C. Hands on what? The relative effectiveness of physical vs. virtual materials in an engineering design project by middle school children. J Res Sci Teach. 2007;44:183–203.

Lawson A. Biology: an inquiry approach. New York: Kendall/Hunt; 2006.

Li J, Klahr D, Siler S. What lies beneath the science achievement gap? The challenges of aligning science instruction with standards and tests. Sci Educ. 2006;15:1–12.

MyDNA. Molecules in motion project at the University of Massachusetts. Available at http://www.bio.umass.edu/biochem/mydna/discovery.html (2003). Accessed 18 Jul 2008.

National Research Council (NRC). Inquiry and the national science education standards: a guide for teaching and learning. 2000. http://books.nap.edu/openbook.php?record_id=9596&page=R1.

National Science Education Standards (NSES). Washington, DC: National Academy; 1995

Novick LR, Catley KM. Understanding phylogenies in biology: the influence of a Gestalt perceptual principle. J Exp Psychol, Appl. 2007;13(4):197–223.

Public Broadcasting System (PBS). On a killers' train: part two: DNA fingerprinting at the Nova Lab. Available at http://www.pbs.org/wgbh/nova/sheppard/analyze.html (2008). Accessed 26 Oct 2008.

Quintana C, Reiser BJ, Davis EA, Krajcik J, Fretz E, Golan-Duncan R, et al. A scaffolding design framework for software to support science inquiry. J Learn Sci. 2004;13(3):337–86.

Raven PH, Johnson GB, Losos J, Singer S. Biology. 7th ed. New York: McGraw-Hill; 2005.

Rezba RJ, Auldridge T, Rhea L. Teaching and learning basic science skills. 1999. Retrieved January 2, 2008, from www.doe.virginia.gov/VDOE/Instruction/TLBSSGuide.doc.

Rutledge ML, Mitchell MA. High school biology teachers' knowledge structure, acceptance & teaching of evolution. Am Biol Teach. 2002;64:21–8.

Shtulman A. Qualitative differences between naïve and scientific theories of evolution. Cogn Psychol. 2005;52:170–94.

Sinatra GM, Brem SK, Evans EM. Changing minds? Implications of conceptual change for teaching and learning about biological evolution. Evo Edu Outreach. 2007;1(2):189–95.

Toth EE. "Virtual inquiry" in the science classroom: what is the role of technological pedagogical content knowledge? Int J Info & Commun Technol Edu. 2009a;5(4), Oct-Dec.

Toth EE. Social supports for inquiry learning with virtual laboratories: evidence from two studies. Proceedings of the National Association for Research on Science Teaching, Orange Grove: CA; 2009b.

Toth EE, Morrow BL, Ludvico LR. Designing blended inquiry learning in a laboratory context: a study of incorporating hands-on and virtual laboratories. Innov Higher Educ. 2008;33(5):333–44.

Wallace R, Soloway E, Krajcik J, Bos N, Hoffman J, Hunter HE, et al. ARTEMIS: learner-centered design of an information-seeking environment for K-12 education. Proceedings of the SIGCHI conference on Human factors in computing systems. Los Angeles, CA; 1998.