Almost all living organisms, including plants, fungi, insects, and humans, have DNA. Variation in DNA, or genetic variation, is responsible for most of the diversity we see in nature. For example, the difference between a house fly and a blue whale or between blue eyes and brown eyes in humans is caused by genetic variation. Like fingerprints, every individual (except for identical twins) has unique DNA. We have found that it is often difficult for students to accept that all organisms (plants, animals, microbes) have DNA.

By analyzing DNA, it is possible to create a DNA fingerprint that is unique to an organism. DNA fingerprinting is used in several disciplines of science, including forensics (as seen on the TV show *CSI: Crime Scene Investigation*), the study of disease transmission, the production of biofuels, and the study of biodiversity.

DNA fingerprints can be created by using restriction enzymes and gel electrophoresis. As biology graduate students working in middle school science classrooms, we are always trying to find creative ways to help students understand science and incorporate research practices. Simulations expose students to research methods even if a certain technology—in this case, the technology required to conduct gel electrophoresis—is unavailable. In this paper, we review DNA fingerprinting and describe two standards-based lessons (see Figure 1 for alignment of activities to the standards) we have used in middle school science classes to provide a hands-on approach to learning the basic idea of how restriction enzymes work, the fundamentals of gel electrophoresis, and the resulting DNA fingerprint.
Assessment of student understanding can be measured using data collected from the creation of a class gel, class discussions, teacher observations, and student reports. The student Activity Worksheet could also be used as an assessment tool. Students should know that DNA is a molecule found in their cells and that, in humans, half comes from each parent. It is the combination of DNA from our mom and dad that makes each of us unique.

The first activity allows students to create a strand of DNA by providing information about themselves on a strip of paper. This strip of personal information represents their DNA. They then cut their strand with “restriction enzymes” (scissors) and place the resulting DNA fragments on a classroom gel, which is represented by Figure 2. Students compare their DNA fragments with those of their classmates and recognize that each person’s DNA is different. Next, students classify their personal information as genetically based, environmentally based, or a genetic trait that is influenced by the environment.

More advanced students will recognize the role of restriction enzymes in cutting the DNA at specific sites, which results in differing DNA fragments. This creates a pattern, which is unique for each individual and is called a DNA fingerprint.

In the second activity, students model the effect of DNA fragment size on movement through a gel, state the relationship between DNA fragment size and movement through a gel, and predict what happens if the gel composition is altered.
Activity 1
We used an assessment probe called “Baby Mice” (Keeley, Eberle, and Tugel 2007) to quickly determine what students already know about heredity. In this probe, students are given a situation in which a pet mouse has seven babies (five are black and two are white). Students were provided with various ideas about how this could occur and were then asked which of the ideas they agree with and why.

Materials
• pencils
• scissors (one set of six scissors per small group):

Preparation
1. Prepare for the activity by printing out the DNA strand template (Figure 3). Because a complete

FIGURE 1  Alignment of activities to National Science Education Standards (NRC 1996) at the middle school level

<table>
<thead>
<tr>
<th>Standard</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Life science content. Reproduction and heredity. Every organism requires a set of instructions for specifying its traits. Heredity is the passage of these instructions from one generation to another (p. 157).</td>
<td>Activity 1</td>
</tr>
<tr>
<td>Life science content. Reproduction and heredity. Hereditary information is contained in genes, located in the chromosomes of each cell. Each gene carries a single unit of information. An inherited trait of an individual can be determined by one or by many genes, and a single gene can influence more than one trait. A human cell contains many thousands of different genes (p. 157).</td>
<td>Activity 1</td>
</tr>
<tr>
<td>Life science content. Reproduction and heredity. The characteristics of an organism can be described in terms of combination of traits. Some traits are inherited and others result from interactions with the environment (p. 157).</td>
<td>Activity 1</td>
</tr>
<tr>
<td>Science as inquiry. Abilities necessary to do scientific inquiry. Formulate and revise scientific explanations and models using logic and evidence (p. 175).</td>
<td>Activities 1 and 2</td>
</tr>
<tr>
<td>Science as inquiry. Abilities necessary to do scientific inquiry. Oral/written reports that present the results of their inquiries (p. 144).</td>
<td>Extension</td>
</tr>
<tr>
<td>Science as inquiry. Abilities necessary to do scientific inquiry. Communicate scientific ideas (p. 144).</td>
<td>Activities 1, 2, and extension</td>
</tr>
<tr>
<td>Science as inquiry. Abilities necessary to do scientific inquiry. Use appropriate tools and techniques to gather, analyze, and interpret data. The use of computers for the collection, summary, and display of evidence is part of this standard (p. 145).</td>
<td>Extension</td>
</tr>
<tr>
<td>Science in personal and social perspectives. Science and technology in society. Technology influences society through its products and processes. Technology influences the quality of life and the ways people act and interact. Technological changes are often accompanied by social, political, and economic changes that can be beneficial or detrimental to individuals and to society. Social needs, attitudes, and values influence the direction of technological development (p. 169).</td>
<td>Extension</td>
</tr>
</tbody>
</table>

Each scissor represents a restriction enzyme. Afix one of the following labels to each pair of scissors: bl, er, ia, hr, sc, and nn.

• DNA strand template (one per student) (see Figure 3 for instructions on creating the template)
• a blank classroom gel (projected onto the board or a SMART Board; created using butcher paper and tape; or drawn on the board) (see Figure 4)
• Activity Worksheet (one per student)
strand will not fit onto one page, you will need to make copies of the template strand, cut them on the dotted line, and tape them together as described in Figure 3. Each student should have a strand that has been made by combining three different smaller strands.

2. Prepare your classroom gel (Figure 4). Depending on the size of your class and the gel you have prepared, you can modify the print size of the DNA strands to make sure there is enough room for any long fragments students have.

Procedure
Students will complete their DNA strand by filling in personal/unique information. Then they will cut their DNA strand into fragments based on the restriction enzymes. Each restriction enzyme (scissors) recognizes a specific site or series of letters. For example, the first restriction enzyme recognizes the site bl. Students will scan their unique strip of DNA and, using the scissors labeled “bl,” cut between the letters b and l every time they see bl. Note: It can only be bl, not lb, because restriction enzymes move unidirectionally. The restriction enzymes are bl, er, ia, hr, sc, and nn. A different pair of scissors is used to represent each restriction enzyme. It is helpful to remind students to select the scissors that correspond to each restriction enzyme listed in the procedure. Complete the first cut as a group, and then students can proceed cutting with other restriction enzymes at their own rate.

Students will place fragments on the community gel based on fragment size. The longest pieces should be

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**FIGURE 2** Arial view of classroom gel

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**FIGURE 3** DNA template strand

Teacher note: The DNA template strands need to be prepared before beginning the lesson. Copy the template strand and cut along the dotted lines. Tape the end of the strand with X1 to the strand beginning with “color.” Next tape the end of the strand with X2 to the strand beginning with “subject.” Finally, cut off the end of the strand at X3. The result is one long strand that is approximately one meter long. See Figure 6. All students should have their own complete strand. Students will fill in the blanks with their personal information and then use restriction enzymes (scissors) to cut at these combinations of letters: bl, er, ia, hr, sc, nn.

My name is ___________________________. I live on ___________________________ street.

My hair is ___________________________ color. My eyes are ___________________________.

I am ___________________________ inches tall. I ___________________________ roll my tongue.

My favorite subject is ___________________________ and my favorite food is ___________________________.

---
placed at the top of the gel and the shortest at the bottom. Discuss results of the community gel by posing the following questions to students (answers in italic):

1. **What do you observe?** *Each student’s pattern is different.*

2. **Why do different restriction enzymes give you different DNA fragment sizes?** *Each student had a different sequence of letters because the blanks on the DNA template strand were filled in with different information. The scissors cut the DNA at specific sites, or letter sequences, which results in different fragment sizes.*

3. **What was the role of the scissors, or restriction enzymes?** *To reveal differences in DNA samples by cutting between a specific series of letters.*

4. **Which information on the DNA template strand is derived from genetics, environmental factors, or a combination of both?** *After students have responded, have a discussion about the interconnectivity of genetics and the environment:*
   - Name and street location are environmentally based.
   - Hair color is genetically derived and exhibits a broad range of phenotypic variation. There are a large number of alleles involved, as well as other genes that control the amount of brown pigment present. It is possible for two red-haired parents to have children who do not have red hair (McDonald 2011). Environmental factors including Sun exposure can affect hair color.
   - Eye color is based on genetics; however, if you look around at the eye color of students in the class, you will notice that not all blue eyes are identical and that some brown eyes are dark and uniform in color whereas others have hints of green or gray. This is because at least 10 genes and many interactions are involved in the determination of eye color (OMIM 1986). Eye color is inherited as a polygenic trait. Because of the complicated nature of the inheritance of eye color, it is possible for two blue-eyed parents to have a child with brown eyes.
   - Height is genetic and environmentally based. There are multiple genes involved (polygenic), hence the variation in tallness that can be observed in families. Height can be influenced by the timing of pubertal growth and nutrition (OMIM 2010).
   - Tongue rolling is influenced by both genetics and the environment. Scientists have conducted studies with identical twins and found that one could tongue roll and the other could not, which can only be explained by environmental factors (identical twins have identical DNA) (McDonald 2011). Note: If students bring up intelligence, it is polygenetic and influenced by both genetics and the environment. Twin DNA is a double-stranded molecule composed of phosphates, deoxyribose sugar, and nitrogenous bases. This phenomenal molecule contains all the information that shapes an organism. There are four nitrogenous bases: adenine (A), thymine (T), guanine (G), and cytosine (C). Although all organisms have the same four bases, the arrangement varies, and it is the order of these bases that is responsible for our uniqueness.

   Enzymes are proteins that have a multitude of essential functions. Restriction enzymes are a specific type of enzyme that acts as chemical scissors to cut DNA at specific sequences. Each restriction enzyme will cut the DNA only when a certain sequence of bases occurs. The number of DNA fragments formed after digestion by an enzyme will depend on the number of times the particular sequence of bases occurs. A common use for restriction enzymes is to generate a fingerprint of a DNA molecule.

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**FIGURE 4** Community gel
studies reveal that the variation in intelligence is 50% genetic and 50% environmental (OMIM 1999).

5. What is gel electrophoresis? *A technique to analyze DNA samples.*

6. Why are the long fragments at the top of the gel and the short fragments at the bottom? *Students probably will not know. This is an excellent lead-in to the next activity, which will answer this question.*

### Activity 2

In the second activity, students will model the effect of fragment size on movement, state the relationship, and predict what happens as the gel composition is altered.

### Materials

- masking tape across the length of one end of the classroom to represent the end of the gel (a “finish line”)

### FIGURE 5

**Research topics and resources**

<table>
<thead>
<tr>
<th>Topic</th>
<th>Suggested website</th>
</tr>
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<tbody>
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<td>African Lemba tribesmen</td>
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<td>Art</td>
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<td>Genetic engineering</td>
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<td>maternity/paternity)</td>
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<tr>
<td>Romanovs</td>
<td><a href="http://www.dnai.org/d/">www.dnai.org/d/</a></td>
</tr>
</tbody>
</table>

### FIGURE 6

**Completed DNA template strand**

My name is __________________________. I live on __________________________ street.

My hair is __________________________ color. My eyes are __________________________

I am __________________________ inches tall. I __________________________ roll my tongue.

My favorite subject is __________________________ and my favorite food is __________________________.
Activity Worksheet: Genes are us

Materials
- pencils
- scissors
- DNA template strand

Safety note: Take appropriate precautions with scissors.

Procedure

1. Complete the DNA strand by filling in the blanks with the correct information—write in your name, eye color, etc. When the answer is a number, write it out in words, such as one or five.

2. After filling in your DNA strand, use scissors to cut specific sequences of letters. The sequence of letters is where the restriction enzyme will cut the DNA. Look on your DNA strand for the letters bl. Cut between the b and l every time you see them together in your DNA strand. It can only be bl, not lb.

3. Examine the DNA strand again and look for the letters ry. Cut between the r and y every time you see them together. Repeat with ia, er, hr, sc, and nn.

4. Place the DNA pieces or fragments on the community gel. Put the longest pieces at the top of the gel and shortest at the bottom. In an actual gel, there are indentations along the top where samples of DNA are placed. In this simulation, the wells represent the starting line.

5. Discuss the following questions:
   a. What do you observe? Do you see any similarities or differences among student results?
   b. What was the role of the scissors, or restriction enzymes?
   c. Why do the different restriction enzymes give you different DNA fragment sizes?
   d. Identify which information on the DNA template strand is genetic, environmental, or a combination of both (the environment influences genetic expression).
   e. What is gel electrophoresis?
   f. Why are the long fragments at the top of the gel and the short fragments at the bottom?

• evenly spaced obstacles in the classroom (you can use chairs and desks or be creative by adding large street cones, etc.)

Procedure

Make sure to set (or have students set) ground rules to ensure safety during the activity (i.e., no running, pushing, yelling). One way to prevent dangerous situations is to have students walk heel to toe, which will ensure they are not running. Explain that the classroom is now a gel (like the one that they made on the board) and show them the boundaries of the gel (the starting and finish lines). Separate them into different-size groups (for a class of 22 students: one group of 8, one group of 5, two groups of 3, and 3 students on their own). Each group links hands. Have them line up in their respective linked groups in a row at the edge of the room that is opposite the finish line and tell them that their objective is to walk to the finish line. The single students get to the finish line faster than the larger groups of students, who are not able to navigate the obstacles as well.

When the first student reaches the finish line, tell the class to freeze and have a teacher or designated student artist draw on the board an aerial view of the resulting “gel” (see Figure 2). First the artist draws the gel (classroom) and can include some features of the classroom, including the start and finish lines, for orientation. As the students have frozen in place, the artist should be able to approximate their location in relation to the gel (classroom). The longer strands of DNA (the largest number of students linked together) will move more slowly through the gel (classroom), making their strand closest to the starting line. The short strands represented by single students will be able to move the fastest and will cross the finish line first. Represent the individuals with an X. The largest group would be X-X-X-X-X-X-X, the next-largest group would be X-X-X-X, etc.

Lead a class discussion using the following questions (answers in italic):

1. Do small or large fragments move faster through the gel? Small fragments move more quickly because they can move through the gel more easily—just as the smaller groups of students were able to reach the finish line first.
2. In your own words, explain the relationship between size and movement in the imaginary gel. Small fragments move faster and are located at the end of the gel, and large fragments travel slowly, stopping near the top of the gel.

3. What would happen if you added more or fewer obstacles? With more obstacles, it would take longer to get to the finish line. With fewer obstacles, they would get to the finish line faster. Note: Scientists apply this knowledge when they do research. They change the percentage of agarose (obstacles) in the gel depending on the DNA sample they are investigating.

DNA-based technologies have many applications. For instance, DNA-based fingerprinting tools are being developed to track animal and plant products to ensure that conservation and management policies are being followed. These technologies are used to identify illegally harvested wood species, bush meat from threatened species, and the harvesting of listed seafood species (Baker 2008; Tnah et al. 2010).

DNA fingerprints have also become the primary means of assessing the diversity, identities, and function of microorganisms, which help keep our planet clean. Microbes remove pollutants and toxic chemicals from land, water, and air, and they clean oil spills in the ocean and gasoline leaks from soils to keep our groundwater safe for drinking. DNA technologies are revealing an unprecedented diversity of life invisible to the human eye.

**Extension**

DNA fingerprinting is used in a multitude of disciplines, including math and engineering (i.e., bioinformatics and genetic engineering). Students can learn about the many diverse uses of DNA fingerprinting technology by investigating the topics listed in Figure 5. Students research a topic of interest, create a poster, and then present their findings, which should include social, political, and economic impacts of their topic.

**Conclusion**

It is often difficult for middle school students to conceptualize abstract thought. One technique to help students move from concrete, operational thought to abstract thought is through simulations. We have described two simple activities that help students develop a conceptual understanding of DNA fingerprinting. The first activity helps students realize that individual DNA is unique as well as visualize the role of restriction enzymes in creating a DNA fingerprint and the process in which a fingerprint is made. The second activity is a representation of how DNA migrates through a gel. The extension encourages students to research a topic of interest and learn about some of the many uses of DNA fingerprinting.

**References**


Alexandra Keller, David Smith, Brenda Harrop, Louis Lamit, Melanie Schroer, and Adam Wymore are graduate students in the NSF GK–12 program and Catherine Ueckert (catherine.ueckert@nau.edu) is a professor and President’s Distinguished Teaching Fellow in the Department of Biological Sciences at Northern Arizona University in Flagstaff, Arizona.