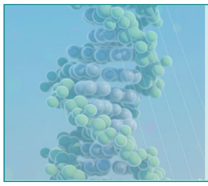

Modeling the Structure of DNA

hhmi BioInteractive

Activity
Educator Materials

OVERVIEW

In this activity, students build a paper model of DNA and use their model to explore key structural features of the DNA double helix. This activity can be used to complement the short film *The Double Helix,* which examines some of the evidence that James Watson and Francis Crick used to determine the double-helical structure of DNA.

KEY CONCEPTS

- DNA is a polymer of nucleotide monomers, each consisting of a phosphate, a deoxyribose sugar, and one of four nitrogenous bases: adenine (A), thymine (T), guanine (G), or cytosine (C).
- The nucleotides of DNA are arranged into a double helix based on the rules of base complementarity.
- Scientists build models based on existing data and use their models to explain and make predictions about natural systems.

STUDENT LEARNING TARGETS

- Build a physical model of the DNA double helix.
- Use a model of DNA to explore and describe key features of the molecule.

CURRICULUM CONNECTIONS

Standard	Curriculum Connections
NGSS (2013)	HS-LS3-1
AP Biology (2015)	3.A.1, 4.A.1; SP1
IB Biology (2016)	2.6, 7.1
Common Core (2010)	ELA.RST.9–12.3
Vision and Change (2009)	CC2

KEY TERMS

deoxyribose, double helix, genetics, model, nitrogenous base, nucleotide, phosphate, phosphodiester bond

TIME REQUIREMENTS

One to two 50-minute class periods, depending on the amount of work assigned as homework.

SUGGESTED AUDIENCE

- High School: AP/IB Biology
- College: Introductory Biology, Molecular Biology, Biochemistry

PRIOR KNOWLEDGE

Students should:

- recognize that the shapes of molecules depend on the arrangement of their component atoms and on the chemical bonds that link them together
- have a basic understanding of the process of DNA replication and the structure of DNA

MATERIALS

- two copies of the paper nucleotides sheet, **printed on heavy card stock**, per student
- scissors
- colored pencils, markers, or crayons
- ruler
- access to the video instructions (optional, but recommended)

TEACHING TIPS

- It is recommended that students watch the short film *The Double Helix* before working on this activity. *The Double Helix* tells the story of the scientific quest to solve the structure of DNA. Much has been written about the ethics of how the credit for this monumental discovery was shared among the scientists who contributed to it (for example, in the book *Rosalind Franklin: The Dark Lady of DNA* by Brenda Maddox). There has also been public controversy about vocal positions that one of the scientists, James Watson, has taken regarding race, as discussed in this *New York Times* article. These issues could become part of your discussion with students. It is important to acknowledge that scientists are people, subject to their personal shortcomings, and accountable for their decisions regarding ethical conduct and personal prejudices.
- The "In-Depth Film Guide" on the film activity page for *The Double Helix* contains extensive information about the history and science of determining DNA's structure. You can review this document for more information about the state of nucleic acid biology in the early and mid-1900s, and for help interpreting the data discussed in the film.
- Provide each student with two sheets of paper nucleotides (the template can be downloaded from this activity's BioInteractive webpage) and a specific four-nucleotide sequence to build.
  - Make sure to print the nucleotide sheets on heavy card stock. Regular paper (for example, 20 lb. bond) is too thin and will not support the model well.
  - Because each sheet has only one of each nucleotide, each student will have only two copies of each nucleotide to work with. Remember this when assigning their four-nucleotide sequences, as the final balance of each nucleotide in their double helix should be equal.
  - Consider providing each student with one or two extra sheets in case they make a mistake.
  - If students wish to build longer nucleotide sequences, you can easily scale up the model-building process. Simply provide them with additional nucleotide sheets and have them use similar instructions.
- Students can use the video instructions to help them build their models.
  - There is one video for each of the six parts in the "Student Handout." Links to the videos are provided in the handout and are as follows: Part 1, Part 2, Part 3, Part 4, Part 5, Part 6.
  - Offline versions of the videos can be downloaded from this activity's BioInteractive webpage.
- In the videos and handout, the nucleotide components are shown in blue, red, yellow, and green. Your class can use alternative colors or methods of distinguishing each component. For example, instead of using colors, they may fill in certain components with specific patterns, such as lines, grids, or polka dots.
- To save classroom time, students may build some, or all, of the model at home. Two approaches are as follows:
  - Students can build their complete four-nucleotide models (Parts 1–5 of the "Student Handout") as homework, which will take them one to two hours. Have students bring their models to class, where they will complete Part 6 and the "Analysis Questions" of the handout.

  - Students can start building their models at home and finish the process in class. You can have them stop the homework component at different points — for example, after coloring and cutting out their nucleotides (Part 1), or after assembling the first strand of their model (Part 3).
- Part 5 of the model-building instructions may be the biggest challenge for students. Check this step carefully if your students are building their models in class. If they are working at home, encourage them to pay close attention to the information in the handout and the video instructions.
  - The way in which the nucleotides of the second strand must be linked to each other may seem counterintuitive, and many students get this step wrong the first time. Students will need to cross the nucleotides over and bend the chain as it grows to ensure that each new nucleotide is linked by its deoxyribose to the phosphate of the previous nucleotide. This ensures that the two strands are antiparallel and introduces the twist necessary for the model's helical structure.
  - If a mistake is made, the links between the nucleotides can be easily undone without tearing.
- This model can be used to teach additional biochemical concepts not covered in the handout. For example, you or your students could:
  - annotate key atoms in the nucleotides, such as the carbon atoms in the deoxyribose, the charged groups in the phosphate, or key hydrogen and nitrogen atoms in the nitrogenous bases
  - label the atoms involved in phosphodiester bonds and hydrogen bonds
  - explore the chemical basis for the 5′ and 3′ nomenclature used in describing nucleic acids
  - point out molecule-wide structural features — such as the major groove, the minor groove, or the number of base pairs per turn — that are visible in long models
- It may be useful to point out some of the model's limitations, or to have students compare and contrast their models with the actual structure or synthesis of DNA (as in Question 6 of the "Student Handout").
  - For example, cells do not synthesize DNA in the same way that students built their models in this activity. In cells, DNA strands grow in the 5′ to 3′ direction by extending existing stretches of nucleic acid. In the model instructions, the second strand is built in the 3′ to 5′ direction, and both strands are built fully from free nucleotides. However, you can modify the model-building instructions to more closely reflect the way that DNA is synthesized.
- The model may lose shape over time, especially as it is examined or manipulated. You can fix this by creasing the folds on each nucleotide again to keep them crisp.
- The model should be easy to use for presentations or demonstrations while it is lying flat. If you would like to display it vertically, you can do so with magnets or tacks on the inside of every fifth deoxyribose ring (as in Figure 1a). Alternatively, a chemistry ring stand with rings separated by about 13 cm will support the structure and help it keep its shape (as in Figure 1b).

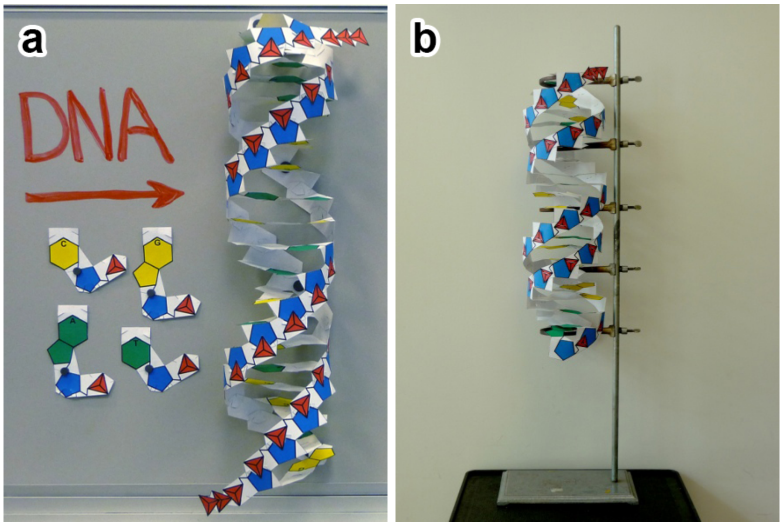

Figure 1. Displaying the DNA paper model.

ANSWER KEY: ANALYSIS QUESTIONS

1. To create the second strand of the model, you linked nitrogenous bases that were "complementary" to each other. What are the two pairs of complementary bases in DNA?
   A is complementary to T, and C is complementary to G.

2. One attribute of real DNA, first revealed by Rosalind Franklin's data, is that the distance between the two strands of DNA (the diameter of the DNA molecule) is approximately the same throughout the helix.

   a. Use a ruler to measure the distance between the two strands of your DNA model at four different points of your choice. Record your measurements below (rounded to the nearest 0.1 cm), then calculate the average diameter of your model.
   Answers will vary. Ideally, all the measurements will be similar. Below are some examples obtained by measuring the distance between the gray dotted lines of paired nucleotides. The nucleotides are folded along this line during Step 1d.

Measurement	Diameter (cm)
1	***15.6***
2	***15.5***
3	***15.4***
4	***15.4***
Average	***15.5***

   b. Does your model have an approximately constant diameter? Explain your answer.
   Answers may vary. Ideally, the model will have an approximately constant diameter. Students should point to the measurements they collected in Question 2a.

   c. Examine the structure of each nitrogenous base: A, T, C, and G. Record below the number of cyclical rings (shown as pentagons or hexagons in the model).

Base	Number of Rings
A	***2***
T	***1***
C	***1***
G	***2***

   d. Based on your answers to Question 2c, how do the rules of complementarity (base-pairing rules) in Question 1 influence the diameter of the double helix?
   The rules of complementarity keep the diameter of the double helix constant. Because A (2 rings) pairs with T (1 ring) and G (2 rings) pairs with C (1 ring), there is always a 2-ring base linked to a 1-ring base, so the width of the helix stays the same all throughout its length.

   e. As described in the film *The Double Helix*, James Watson once thought that the nitrogenous bases were paired in a "like-with-like" pattern (adenine with adenine, cytosine with cytosine, and so on). If this were true, would DNA have a constant diameter? Explain your answer.
   No, DNA would not have a constant diameter. The pairs of bases with 2 rings (A-A, G-G) would be wider, and the pairs of bases with 1 ring (T-T, C-C) would be narrower.

3. The film *The Double Helix* claims that DNA is asymmetrical, with the two strands running in opposite (antiparallel) directions. Use specific evidence from your model to support this claim.

Example answer: One of the model's strands begins with a free phosphate and ends with a deoxyribose. In the other strand, the free phosphate and deoxyribose are on opposite ends. So the strands run in opposite directions.

4. If many double helix models, each with a different sequence, are separated into their two strands and the single strands are mixed together in a drawer, could you reassemble all the original double helices? Explain your answer.
   Example answer: Yes, I could use the base-pairing rules to find the complementary sequence for any given strand. I could then pair all the complementary strands back together.

5. Imagine that two people must each copy an existing double helix model. They can each take one strand of the model, but cannot see each other's work or communicate with one another. Could they build two identical copies of DNA? How would this process model the replication of DNA in cells?
   Example answer: Each person could take one strand of the existing model, then use base-pairing rules to build the complementary strand. The result would be two identical double helices. In cells, DNA in chromosomes is also separated into two strands, and each strand is used as a template or guide for making a complementary strand. The result is also two copies of the same sequence of DNA.

6. All scientific models have both strengths and limitations. Describe three characteristics of DNA that are well represented by your model and three that are not.
   Example answer: Three characteristics of DNA that are well represented by this model are its antiparallel structure, its double-helical shape, and its constant diameter. Three characteristics that are not well represented are the size of real DNA, the fact that other molecules (like proteins and water) are often present with DNA, and the fact that DNA is very flexible and can be tightly packed without being damaged.

REFERENCES

Franklin, Rosalind E. and R. G. Gosling. "Molecular Configuration in Sodium Thymonucleate." *Nature* 171, 4356 (1953): 740–741. https://doi.org/10.1038/171740a0.

Watson, J. D. and F. H. C. Crick. "Molecular Structure of Nucleic Acids: A Structure for Deoxyribose Nucleic Acid." *Nature* 171, 4356 (1953): 737–738. https://doi.org/10.1038/171737a0.

Wilkins, M. H. F., A. R. Stokes, and H. R. Wilson. "Molecular Structure of Nucleic Acids: Molecular Structure of Deoxypentose Nucleic Acids." *Nature* 171, 4356 (1953): 738–740. https://doi.org/10.1038/171738a0.

AUTHORS

Kirt Moody, PhD, Columbia College, Columbia, SC; Javier Robalino, PhD, HHMI; Mary Colvard, Cobleskill-Richmondville High School (retired), Nottingham, NH

DNA paper model created by Kirt Moody, Columbia College, Columbia, SC

Edited by Paul Beardsley, PhD, Cal Poly-Pomona; Esther Shyu, PhD, HHMI