

DNA Function, Structure and Replication – Teacher Notes¹

In this analysis and discussion activity, students learn the basics of DNA function, structure, and replication. The sequence of nucleotides in a gene determines the sequence of amino acids in a protein, which determines the structure and function of the protein. Different versions of a gene give the instructions to make different versions of a protein, which can result in different characteristics. Since many different proteins are needed for a cell to be alive, each cell needs a complete copy of the DNA with all of the genes. Therefore, before a cell divides, it needs to make a copy of all its DNA. Students analyze DNA replication to understand how the double helix structure of DNA, the base-pairing rules, and DNA polymerase work together to produce two identical copies of the original DNA molecule.

Before students begin the activity, it will be helpful if they have a basic understanding of the structure and functions of proteins. For this purpose, I recommend "Introduction to the Functions of Proteins and DNA" (<https://serendipstudio.org/exchange/bioactivities/proteins>).

We estimate that this activity will require at least one 50-minute period, depending on your students and how much they know about DNA before beginning this activity.

If you want to include a hands-on extraction of DNA, you can combine this analysis and discussion activity with extraction of DNA from strawberries (<https://sites.google.com/view/biologypd-home/topics/biological-molecules>) or you can use "DNA", an activity in which students extract DNA from cheek cells or from the archaeon, *Haloferax volcanii* (https://serendipstudio.org/sci_edu/waldron/#dna).

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Learning Goals

In accord with the Next Generation Science Standards²:

- Students will gain understanding of the Disciplinary Core Ideas:
 - LS1.A, Structure and Function, "All cells contain genetic information in the form of DNA molecules. Genes are regions in the DNA that contain the instructions that code for the formation of proteins."
 - LS3.A, Inheritance of Traits, "Each chromosome consists of a single very long DNA molecule, and each gene on the chromosome is a particular segment of that DNA. The instructions for forming species' characteristics are carried in DNA."
- Students will engage in the Scientific Practice, "Constructing Explanations. Apply scientific ideas, principles and/or evidence to provide an explanation of phenomena..."

¹ By Dr. Ingrid Waldron, Department of Biology, University of Pennsylvania, 2023. These Teacher Notes and the related Student Handout are available at <https://serendipstudio.org/exchange/bioactivities/DNA>.

² Quotations from <http://www.nextgenscience.org/sites/default/files/HS%20LS%20topics%20combined%206.13.13.pdf>

- This activity provides the opportunity to discuss the Crosscutting Concept, "Structure and Function. The functions and properties of natural and designed objects and systems can be inferred from their overall structure, the way their components are shaped and used, and the molecular substructures of its various materials."
- This activity helps to prepare students for the Performance Expectation, HS-LS1-1, "Construct an explanation based on evidence for how the structure of DNA determines the structure of proteins which carry out the essential functions of life..."³

Additional Content Learning Goals

- DNA carries the genetic information in all types of organisms. Each DNA molecule contains multiple genes.
- A DNA molecule has two strands of nucleotides wound together in a double helix. Each nucleotide is composed of a phosphate group, a sugar molecule, and one of four different bases: adenine (**A**), thymine (**T**), guanine (**G**), or cytosine (**C**). The phosphate and sugar parts of the nucleotides form the backbone of each strand in the DNA double helix.
- The bases extend toward the center of the double helix, and each base in one strand is matched with a complementary base in the other strand. In accord with the base-pairing rules, **A** pairs with **T** and **G** pairs with **C**.
- Proteins are polymers of amino acids. The specific sequence of amino acids determines the structure and function of the protein. Proteins have many important functions in cells, including protein enzymes that catalyze chemical reactions and transport proteins.
- The sequence of nucleotides in a gene gives the instructions for the sequence of amino acids in a protein. A difference in the sequence of nucleotides in a gene can result in a different sequence of amino acids which can alter the structure and function of the protein. This can result in different characteristics, e.g., albinism vs. normal skin and hair color.
- DNA replication produces two new DNA molecules that have the same sequence of nucleotides as the original DNA molecule; thus, each of the new DNA molecules carries the same genetic information as the original DNA molecule. During DNA replication, the two strands of the original DNA double helix are separated and each old strand is used as a template to form a new matching DNA strand. The enzyme DNA polymerase adds nucleotides one-at-a-time, using the base-pairing rules to match each nucleotide in the old DNA strand with a complementary nucleotide in the new DNA strand.

Instructional Suggestions and Additional Information

To maximize student learning and participation, I recommend that you have your students work in pairs to answer each group of related questions. Student learning is increased when students discuss scientific concepts to develop answers to challenging questions. After your students have answered each group of related questions, I recommend that you have a class discussion to probe student thinking and help students develop a sound understanding of the concepts and information covered. In order to consolidate accurate understanding, you may want to offer students the opportunity to prepare revised versions of their answers to key questions.

If your students are learning online, I recommend that they use the Google Doc version of the Student Handout available at <https://serendipstudio.org/exchange/bioactivities/DNA>. To answer questions 4 and 7, students can either print the relevant pages and send pictures of their answers to you, or they will need to know how to modify a drawing online. To answer online, they can

³ This activity also helps to prepare students for the middle school Performance Expectation, MS-LS3-1, "Develop and use a model to describe why structural changes to genes located on chromosomes may affect proteins and may result in harmful, beneficial, or neutral effects to the structure and function of the organism."

double-click on the relevant drawing in the Google Doc to open a drawing window. Then, they can use the editing tools to answer the questions.⁴

If you use the Word version of the Student Handout to make changes for your students, please check the PDF version to make sure that the formatting of the Word version displays correctly on your computer.

A key is available upon request to Ingrid Waldron (iwaldron@upenn.edu). The following paragraphs provide additional instructional suggestions and background information – some for inclusion in your class discussions and some to provide you with relevant background that may be useful for your understanding and/or for responding to student questions.

DNA Function, part 1

Question 1 will help students recall their previous learning about DNA, and a class discussion of their answers will help you to understand your students' current knowledge of DNA, including any misconceptions they may have.

To ensure student understanding in this introductory activity, the Student Handout includes multiple simplifications. For example, the definition of a gene on page 1 in the Student Handout ignores multiple complexities, including the facts that many genes code for more than one polypeptide and many genes code for RNA that has different functions from mRNA (e.g., ribosomal RNA and regulatory RNA).

You will want to be sure that your students understand that DNA carries the genetic information in all types of organisms, and the basic function and structure of DNA is similar in all types of organisms.

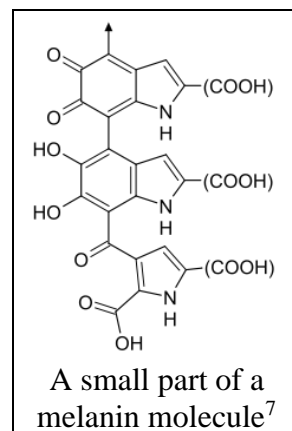
Question 2 discusses genes that are crucial for the cells to survive; if a version of one of these genes gives instructions to make a nonfunctional version of the protein, this would result in cell death.⁵ In contrast, the table near the bottom of page 1 of the Student Handout describes an example of a gene that is not crucial for cell survival; therefore, an allele of this gene that codes for a nonfunctional version of the protein enzyme is not lethal and instead can result in albinism.⁶

⁴ To draw a shape, (1) At the top of the page, find and click Shape; (2) Choose the shape you want to use; and (3) Click and drag on the canvas to draw your shape. When you are done, click Save and Close.

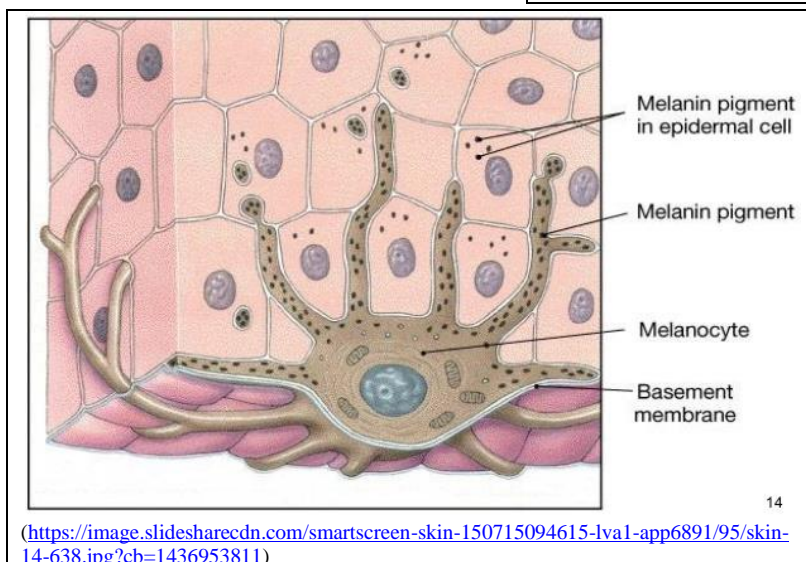
⁵ Although DNA with genes is required to give the instructions for making proteins, not all cells have DNA. For example, mature red blood cells do not have DNA because they have ejected their nuclei after hemoglobin and other proteins have been synthesized.

⁶ Since this allele is recessive, a person would be albino only if both copies of the gene coded for a nonfunctional version of the protein enzyme; this complexity is not discussed in this learning activity, but instead is discussed in "Genetics" (https://serendipstudio.org/sci_edu/waldron/#genetics) or "Introduction to Genetics – Similarities and Differences between Family Members" (<https://serendipstudio.org/exchange/bioactivities/geneticsFR>).

The allele for albinism codes for a defective enzyme (tyrosinase) for producing melanin, a dark pigment that protects skin cells' DNA from the damaging effects of the sun's UV radiation. In the most common form of albinism, the defective enzyme for producing melanin not only results in albino skin and hair color, but also affects the appearance and function of the eyes.



Melanin is produced in melanosomes inside melanocytes and transported into the epidermal cells in the outer layers of the skin. A good explanation is provided in the short video, “How We Get Our Skin Color”.⁸



After question 3 you may want to ask your students the question shown below. This question will alert your students that skin color is influenced by other genes (e.g., genes that influence how much melanin is made) and environmental factors (e.g., sun exposure which can result in increased production of melanin).⁹

4a. Based on what you know about human skin color, are these two versions of a gene the only factors that influence skin color? no ___ yes ___

4b. Explain your reasoning.

Further information about albinism is available at <https://medlineplus.gov/ency/article/001479.htm> and <https://omim.org/entry/203100>.

DNA Structure

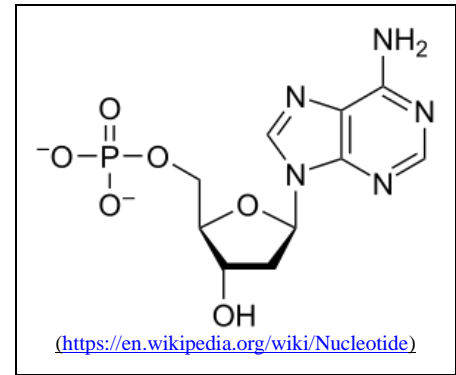
For the right-hand diagram in the top figure on page 2 of the Student Handout, you may want to ask your students about the difference between the solid lines (which represent covalent bonds

⁷ <https://upload.wikimedia.org/wikipedia/commons/thumb/3/3a/Eumelanine.svg/220px-Eumelanine.svg.png>

⁸ Available at <http://www.hhmi.org/biointeractive/how-we-get-our-skin-color>.

⁹ These points are developed in “Were the babies switched?” (https://serendipstudio.org/sci_edu/waldron/#blood).

within each DNA strand) and the dotted lines (which represent hydrogen bonds between the two strands). As shown in the Student Handout, each nucleotide consists of a deoxyribose sugar, a phosphate group and one of four nitrogenous bases. This figure shows additional detail of a nucleotide that contains the nitrogenous base, adenine (A). The nitrogenous bases can accept a positive hydrogen ion, which explains why they are called bases (<https://www.quora.com/Why-are-adenine-thymine-cytosine-and-guanine-called-bases>).

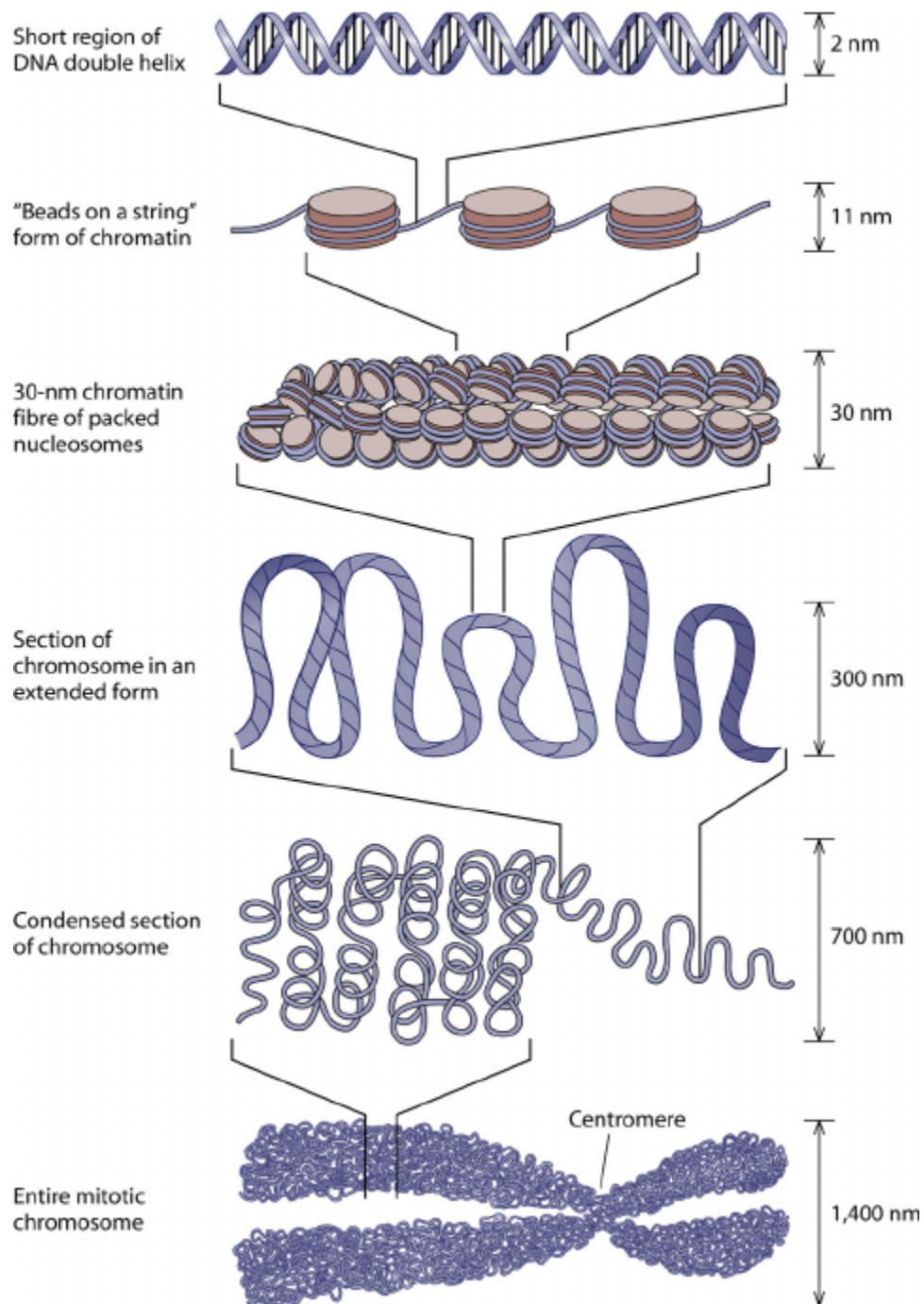


You may want to explain to your students that DNA stands for deoxyribonucleic acid. Deoxyribonucleic refers to both the deoxyribose sugar in each nucleotide and the fact that DNA is a polymer of nucleotides. You can explain why DNA is an acid, even though it contains bases; the phosphate groups in the backbone of each DNA strand are acidic and this effect dominates, in part because the phosphate groups are on the outside of the DNA molecule and the bases are hydrogen-bonded in pairs on the inside of the DNA molecule.

The DNA molecule in each human chromosome has between 47 million and 249 million base pairs.¹⁰ A DNA molecule is approximately 2 nm in diameter and roughly 3 cm in length. Thus, a DNA molecule is roughly 10 million times as long as it is wide.

The structure of eukaryotic chromosomes is highly dynamic (see figure below; The Molecular Biology of the Cell, Fifth Edition). During interphase, most of each chromosome is in the chromatin form. These threadlike chromosomes form loops within the nucleus, which has a diameter of only 5-20 μm in eukaryotic cells.

¹⁰ The number of genes per human chromosomes varies from roughly 200 (Y chromosome) to over 3000 (chromosome 1) (<https://www.ncbi.nlm.nih.gov/books/NBK22266/>). Each human cell has 23 pairs of homologous chromosomes. The total number of human genes is estimated to be over 20,000.



(https://www.researchgate.net/profile/Kevin_Verstrepen/publication/51196608/figure/fig1/AS:276923784679429@1443035183356/Chromatin-structure-DNA-is-wrapped-around-a-histone-octamer-to-form-nucleosomes.png)

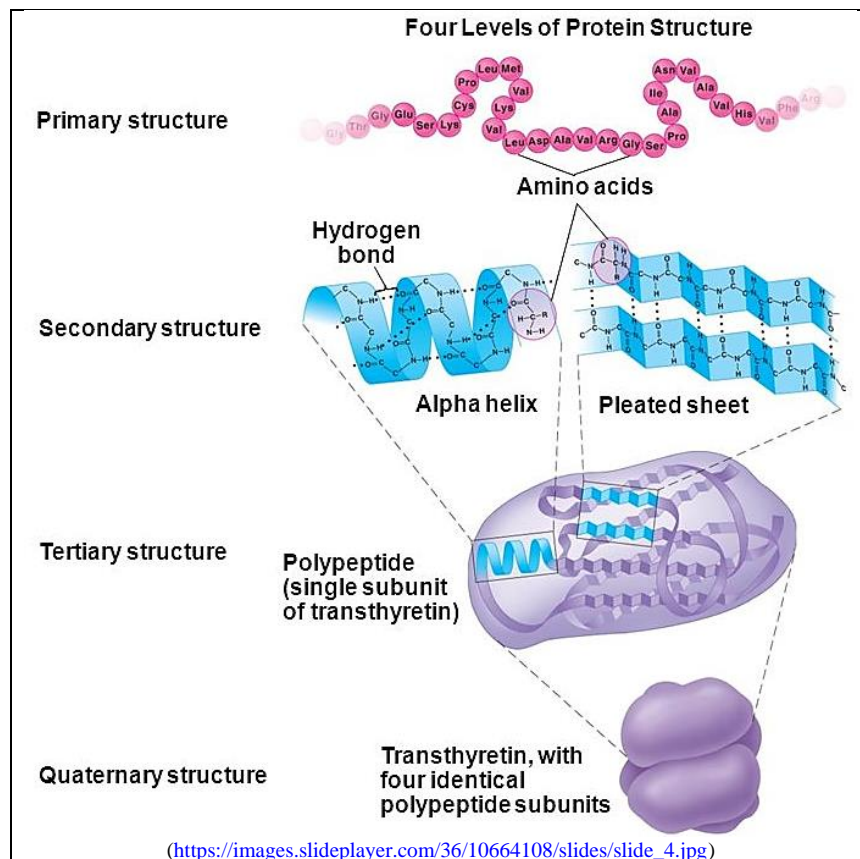
To further develop student understanding of the diagrams of DNA on page 2 of the Student Handout, you may want to include the following question after question 8.

9a. Explain why none of the diagrams show a whole DNA molecule.

9b. In the top figure, circle the part of the double helix on the left that is included in the two diagrams on the right.

DNA Function, part 2

If your students would benefit from a review of protein structure, you may want to use this figure. (Transthyretin is a transport protein that carries the thyroid hormone, thyroxine, and retinol-binding protein bound to retinol.)



Question 9 is crucial for students to understand the function of DNA and why DNA replication needs to preserve the precise sequence of nucleotides. To answer this question, students should combine information from the bottom half of page 1 of the Student Handout and the top half of page 3.¹¹ After a class discussion of student answers, you may want to offer students the opportunity to prepare revised versions of their answers.

If you have not already, you may want to discuss additional examples that illustrate how different versions of a gene can result in different versions of a protein which can result in different characteristics. The table below provides examples; information about each example is available in the Teacher Notes at <https://serendipstudio.org/exchange/bioactivities/proteins>.

Protein Function	Examples	Effect if this Protein is Missing or Defective
Enzyme	Lactase (breaks down lactose)	Lactose intolerance (difficulty digesting milk)
	Acetaldehyde dehydrogenase (breaks down acetaldehyde, a harmful product of alcohol metabolism)	Alcohol sensitivity (skin flushing and unpleasant symptoms after drinking alcohol)
Transport	Hemoglobin	Sickle cell anemia

¹¹ If you want your students to learn more about how the sequence of nucleotides in DNA gives the instructions for the sequence of amino acids in a protein, I recommend our learning activities on transcription and translation (<https://serendipstudio.org/exchange/bioactivities/trans> or https://serendipstudio.org/sci_edu/waldron/#trans).

	(protein in red blood cells which transports oxygen in the blood)	
Clotting	Clotting proteins in blood	Hemophilia (excessive bleeding)

To supplement the explanations in the Student Handout, you may want to show your students the 5-minute [video](https://www.statedclearly.com/videos/what-is-dna/), “What is DNA and how does it work?” (<https://www.statedclearly.com/videos/what-is-dna/>).

DNA Replication

Eukaryotic DNA changes shape during the cell cycle; as a cell prepares for cell division, each chromosome is highly condensed (as shown at the bottom of the figure on page 5 of these Teacher Notes). The figure on the bottom of page 3 of the Student Handout would be more accurate if it showed the chromosomes in a threadlike, more extended form in the initial cell before DNA replication and in the daughter cells produced by cell division; this complexity has been ignored for this introductory learning activity.

To answer [questions 10 and 14](#), students should remember that DNA provides the information to make crucial proteins and the sequence of nucleotides in each gene specifies the sequence of amino acids in each protein which determines the protein’s structure and function. The rate of errors in DNA replication is extremely low (approximately one in a billion nucleotides). DNA replication is highly accurate in part because DNA polymerase “proofreads” each new DNA strand for mistakes and backtracks to fix any mistakes it finds.¹²

You will need to give your students additional instructions for answering [question 12](#).¹³

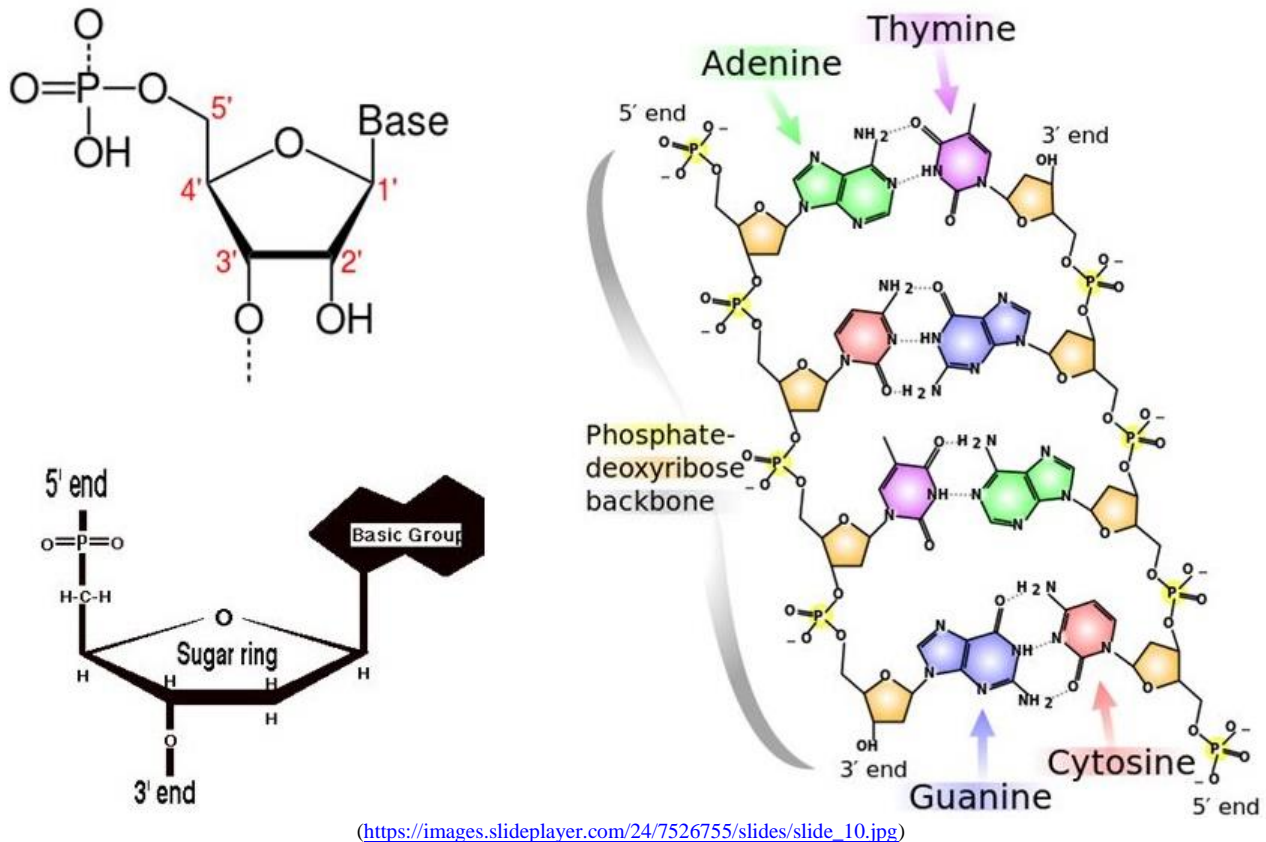
- If your students are learning in your classroom, you can give each student the following supplies.
 - nucleotide pieces – A template for making enough nucleotide pieces for nine students or pairs of students is provided on the last page of these Teacher Preparation Notes. After you photocopy enough copies for the number of students you have, you can:
 - precut each page in nine parts and provide your students with scissors as well as tape or
 - recruit student helpers to precut each page to make 9 packets of 10 nucleotides each.
 - tape
- If you prefer, you can use the online [DNA Replication Simulation](#). This simulation will allow the students to move each individual nucleotide from the table at the bottom of the page to the appropriate location in the drawing of the separated DNA strands.

Students may wonder why the arrows point in opposite directions in the [DNA polymerase](#) figure on page 5 of the Student Handout. To understand this, they first need to know that the DNA strands in a double helix run in opposite directions, based on the orientation of the deoxyribose sugar in the backbone (see figure below). DNA polymerase can only add nucleotides in the 5’ to

¹² Additional repair mechanisms contribute to the accuracy of DNA copies. Nevertheless, sometimes a mistake is made and not found, and then the mistake can become a permanent mutation. Any daughter cells will have this same mutation. A mutation in a gamete that forms a zygote can result in significant effects, such as muscular dystrophy. (See [Mutations and Muscular Dystrophy](#), <https://serendipstudio.org/exchange/bioactivities/mutation/>.) Mistakes in DNA replication during mitosis can contribute to the development of cancer.

¹³ This simulation is adapted from *Instructor Guide to Biology – A Guide to the Natural World* by Jennifer Warner.

the 3' direction. For additional explanation and information, see the second or third videos listed below.



(https://images.slideplayer.com/24/7526755/slides/slide_10.jpg)

DNA polymerase forms a covalent bond between the sugar of the last nucleotide in the new DNA strand and the phosphate of the next nucleotide to be added. DNA polymerase also proofreads each DNA strand for mistakes and backtracks to fix any mistakes it finds. For question 15, if your students are not familiar with the use of the suffix "ase" to designate an enzyme, you will need to provide that information. Before or after question 15, you may want to show your students one of the following videos.

- “DNA Replication Animation by Interact Medical”, a 1-minute video at <https://www.youtube.com/watch?v=zdDkiRw1PdU>. It should be mentioned that the narrator uses strands to refer to both the DNA double helix and the individual strands in a DNA double helix.
- “DNA replication – 3D”, a 3.5 minute video at <https://www.youtube.com/watch?v=TNKWgcFPHqw>. This video provides a more complete description of DNA replication, including an explanation of why and how DNA replication occurs in opposite directions on the two strands and the complications that result.
- “DNA Replication: Copying the Molecule of Life”, a 6-minute video at <https://www.youtube.com/watch?v=9kp9wiYMQUU>. This video also provides a more complete description of DNA replication, including an explanation of why and how DNA replication occurs in opposite directions on the two strands and the complications that result.

Question 16 provides the opportunity for your students to synthesize the information they have learned about DNA replication. You may want to use this more challenging substitute for questions 16a-16c:

16. Explain how the double helix structure of DNA, the base-pairing rules, and DNA polymerase work together to produce two identical copies of the original DNA molecule.

After a class discussion of student answers to question 16, you may want to offer your students the opportunity to prepare revised versions of their answers. Also, you may want to discuss the Crosscutting Concept, Structure and Function. Specifically, the double helix structure of DNA and base pairing provide the basis for DNA replication.

Assessment

After your students have completed the Student Handout, you can assess their understanding of key concepts by having them complete the “DNA Quiz” on page 12 of these Teacher Preparation Notes. After students complete this quiz, you should have a class discussion in which students compare their answers and you provide prompt feedback so they can improve the accuracy and completeness of their answers. This type of active recall with feedback helps to consolidate student understanding and retention of the concepts learned during the activity.¹⁴

Follow-Up Activities and Additional Resources (All the recommended activities are aligned with the [Next Generation Science Standards](#).)

To further develop student understanding of how DNA provides the instructions for protein synthesis and influences our characteristics, we recommend:

– our analysis and discussion activity From Gene to Protein via Transcription and Translation (<https://serendipstudio.org/exchange/bioactivities/trans>)

or

– our hands-on modeling activity From Gene to Protein – Transcription and Translation (https://serendipstudio.org/sci_edu/waldron/#trans).

To help students understand how chromosomes are separated during cell division and how genes are transmitted from parents to offspring, we recommend our mitosis activities and our meiosis and fertilization activities:

– https://serendipstudio.org/sci_edu/waldron/#mitosis

or <https://serendipstudio.org/exchange/bioactivities/MitosisRR>

and

– https://serendipstudio.org/sci_edu/waldron/#meiosis

or <https://serendipstudio.org/exchange/bioactivities/meiosisRR>

Additional background information and suggestions for follow-up activities are provided in:

– Molecular Biology: Major Concepts and Learning Activities
(<https://serendipstudio.org/exchange/bioactivities/MolBio>)

– Genetics – Major Concepts and Learning Activities
(<https://serendipstudio.org/exchange/bioactivities/GeneticsConcepts>).

¹⁴ Evidence for the benefits of active recall with prompt feedback is described in <http://www.scientificamerican.com/article/researchers-find-that-frequent-tests-can-boost-learning/>.

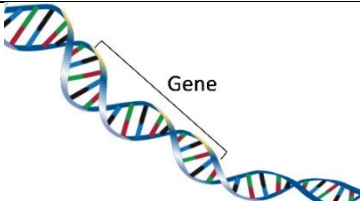
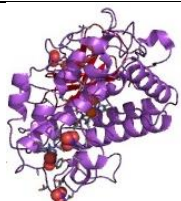

To ensure student understanding of the basics of DNA structure, function, and replication, this activity ignores many complexities. For additional information, see:

- [https://bio.libretexts.org/Bookshelves/Introductory_and_General_Biology/Book%3A_Introductory_Biology_\(CK-12\)/04%3A_Molecular_Biology](https://bio.libretexts.org/Bookshelves/Introductory_and_General_Biology/Book%3A_Introductory_Biology_(CK-12)/04%3A_Molecular_Biology)
- helpful resources available at <https://learn.genetics.utah.edu/content/basics/> and <https://www.biointeractive.org/classroom-resources/teacher-guide-dna>
- videos available at <https://www.biointeractive.org/classroom-resources/chemical-structure-dna> and <https://www.biointeractive.org/classroom-resources/dna-replication-basic-detail>.

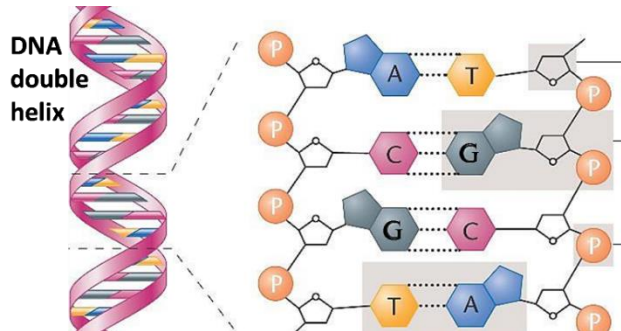
DNA Quiz

Name _____

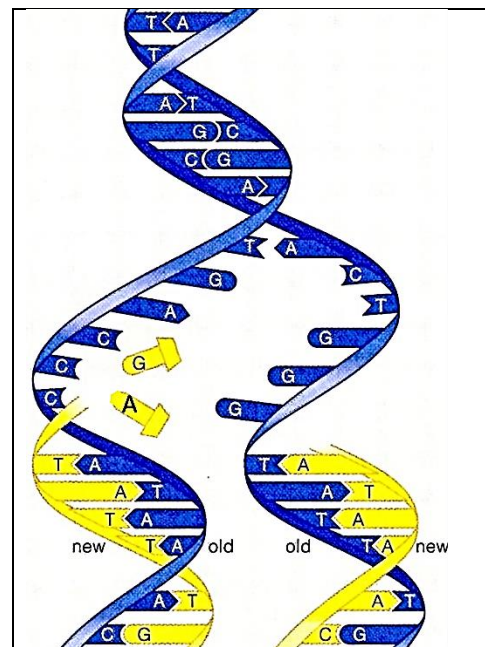
1. Complete this table to describe how two different versions of a gene can result in normal skin and hair color vs. albinism.

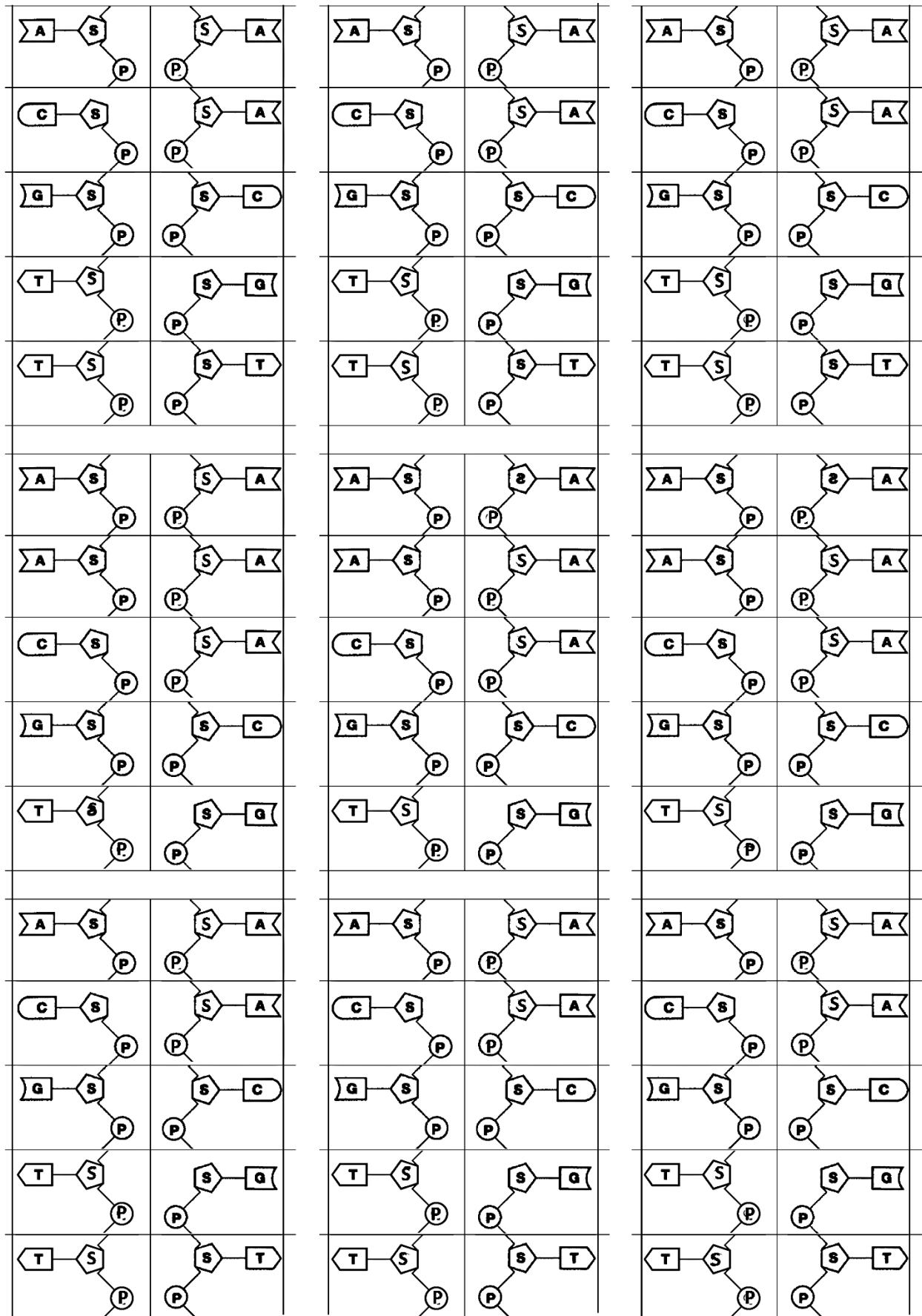
	→		→	
	→		→	
	→		→	Normal skin and hair color
	→		→	Very pale skin and hair = albinism

2. Write sentences and label the figure to describe the structure of DNA.



3. Describe how DNA is replicated.





Nucleotides for Nine Students or Pairs of Students