DNA and RNA

Created with: Release 2022-2

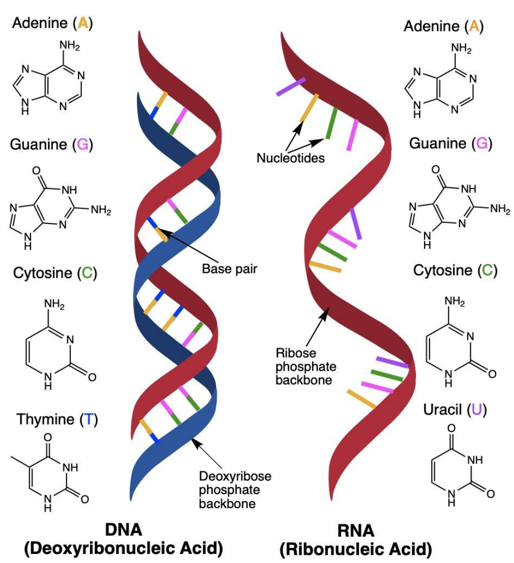
Prerequisites: working knowledge of Maestro

Files Supplied: DNA_RNA_worksheet

Categories: high school biology, AP/college general biology

About this Lesson:

DNA (or Deoxyribonucleic Acid) is the master code of life that is present in nearly all living organisms. When DNA is passed down from parent to child, it can determine how the child looks, like their eye and hair color. However, DNA alone cannot account for the expression of genes. **RNA** (Ribonucleic Acid) is also needed to help carry out the instructions in DNA. In this lesson, you will learn about the molecular structures of DNA and RNA. This is important for learning about genes and the production of amino acids to form proteins. Using Maestro, students will learn how to use the Build Biopolymer function to create DNA and RNA, look at noncovalent bond interactions within the two strands, as well as measure distances between the bases in DNA.



Learning Objectives:

- Break down the molecular structures of DNA and RNA
- Review and dive deeper into the central dogma of molecular biology
- Build and interpret the structure of DNA and RNA using Build Biopolymer from the Protein Preparation and Refinement Panel
- Analyze hydrogen bonding within DNA and RNA from the Maestro graphical user interface
- Generate electrostatic potential surfaces to view a DNA's overall shape
- Calculate distances between the nitrogenous bases using the Measurements panel

Standards:

- *NY State Core Curriculum:*
  - DNA Bonding (Standard 4, Key Idea 5.2)
- *Connections to AP:*
  - Gene Expression and Regulation (IST 1)
- *IB Diploma Programme:*
  - Structures of DNA & RNA (Core Topic 2.6)
- *ACS Guidelines:*
  - Biological Structures and Interactions - (Conceptual Topics)
- *ETS Chemistry GRE:*
  - Organic Chemistry - Nucleic Acids (3F)
- *AAMC MCAT:*
  - Biological and Biochemical Foundations of Living Systems (1B)

Assessments:

The following types of formative assessments are embedded in this lesson:

- Assessment of student understanding through discussion of warm-up questions and filling in any knowledge gaps about the structures of DNA and RNA
- Visual assessment of student-generated DNA double stranded structure, RNA single stranded structure, and measurements of DNA clefts

Warm-Up Questions: To be done on their own or at the beginning of class

Read the Khan Academy article on Nucleic Acids and answer the following questions:

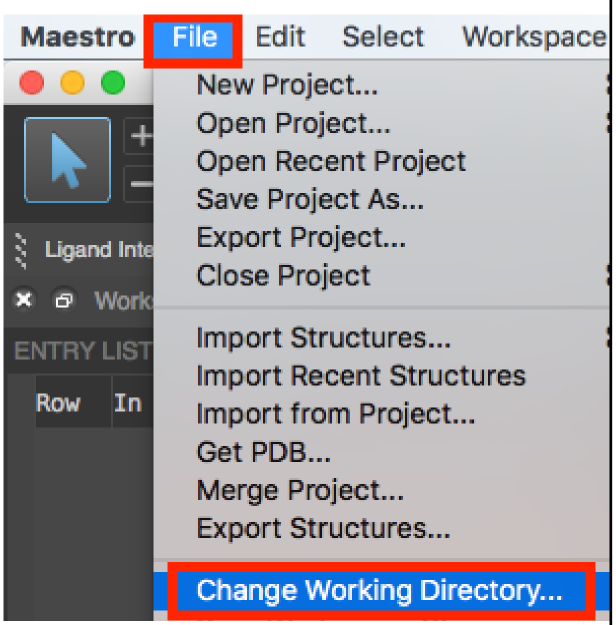
1) What is the basic subunit of DNA and RNA called? What is this subunit made of?

2) What is the difference between a purine and pyrimidine?

3) What is the central dogma of molecular biology?

Lesson Outline:

1. What you will need for this lesson

	1. Go to the 'Data' folder and open your Class Folder found on the virtual cluster's desktop. 2. Right-click on the folder called "DNA_RNA" and copy folder to Desktop • Here, you will find the lesson plan, worksheet, and any additional resources
 *Figure 1-1. Open Maestro.*	3. Open **Maestro** a. See Starting Maestro if you need help
 *Figure 1-2. Change Working Directory option.*	4. Go to **File > Change Working Directory** 5. Find your "DNA_RNA" folder that you duplicated to your Desktop, and click **Choose**

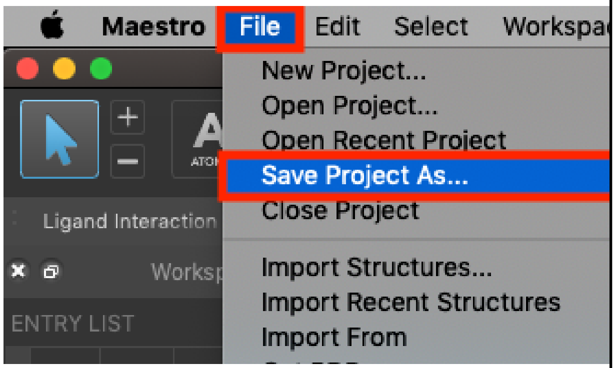


Figure 1-3. Save Project panel.

6. Go to **File > Save Project As**
7. Type "**DNA_RNA_tutorial**" and click **Save**
    a. The project will be titled **DNA_RNA_tutorial.prj**

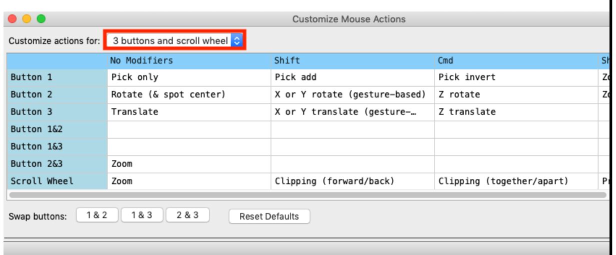


Figure 1-4. Choose the best mouse option for your set up.

8. Finally, check your **Mouse Actions**
    a. PC : **Edit > Customize Mouse Actions**
    b. Mac : **Workspace > Customize Mouse Actions**
9. Make sure you have **the best option chosen for your set up**. This lesson was written with a three-button mouse with a scroll wheel, meaning the scroll wheel is a button as well as a wheel. If you do not have a mouse, choose **Trackpad**.

2. Introduction to DNA Structure

DNA is a **nucleic acid**, which is one of four major groups of biological macromolecules that sustain life. Nucleic acids are composed of **nucleotides.** In DNA, each nucleotide is made up of three main parts: a 5-carbon sugar called deoxyribose, a phosphate group, and a nitrogenous base. There are four types of nitrogenous bases found in DNA: adenine (A), cytosine (C), guanine (G), and thymine (T). To understand how DNA forms into its well-known double helical structure, we have to zoom into DNA's **sugar-phosphate backbone** in **Figure 2-1 below**. The sugar-phosphate backbone consists of a chain of nucleotides linked by covalent bonds called **phosphodiester linkages**, which form between the deoxyribose sugar of one nucleotide and the phosphate group of the next. This arrangement makes up two alternating chains or strands of deoxyribose sugar and phosphate groups in the DNA polymer that run in opposite directions of one another. This results in DNA molecules having an **antiparallel** structure with **complementary** strands: one strand runs from its 5’ end to 3’ end and is paired with a matching strand that runs from its 3’ end to 5’ end.

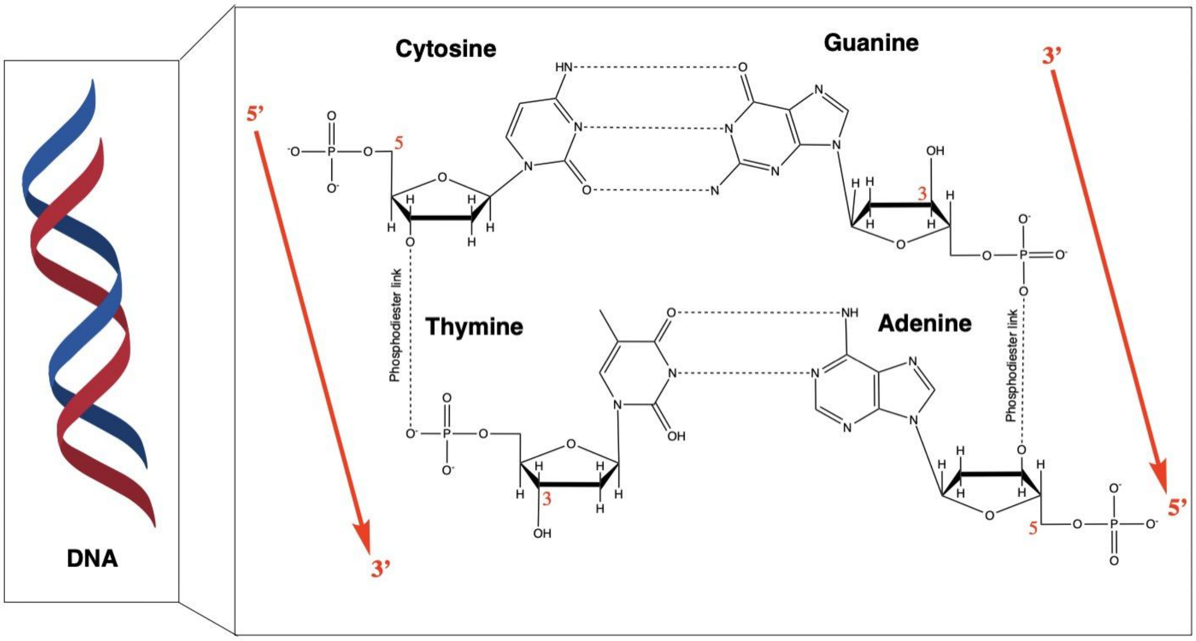


Figure 2-1. Molecular structure of DNA

As you can see in **Figure 2-1**, the sugar-phosphate backbone of the DNA molecule lies on the outside of the helix. At the 5’ end of one DNA strand, the 5’ phosphate group of the first nucleotide sticks out. At the other end, called the 3’ end, the 3’ hydroxyl group sticks out of the last nucleotide in the chain. The nitrogenous bases on the other hand, extend into the interior of the helix and form **base pairs**. Base pairing is highly specific, A can only pair with T and G can only pair with C, and bases are bound together by hydrogen bonds. This means that we can predict the arrangement of bases in the complementary DNA strand for a given strand of DNA. Try it out for yourself in the exercise below!

Example #1. Complete the complementary DNA strand for each given strand of DNA

a. CGTAAGCGCTAATTA

b. TCTTAAATGATCGATC

c. GGCATTCGCGATCATG

3. Introduction to RNA Structure

RNA is a nucleic acid that carries out the instructions coded by DNA. Like DNA, RNA is also made up of nucleotides consisting of a 5-carbon sugar, phosphate group, and nitrogenous base. However, there are three main differences between the structures of DNA and RNA as pictured in **Figure 3-1**. First, RNA uses the sugar *ribose* instead of deoxyribose. In ribose, there is a hydroxyl group on the 2' end of the carbon. Second, RNA is usually *single* stranded not double stranded. Third, RNA replaces the nitrogenous base thymine (T) with *uracil* (U).

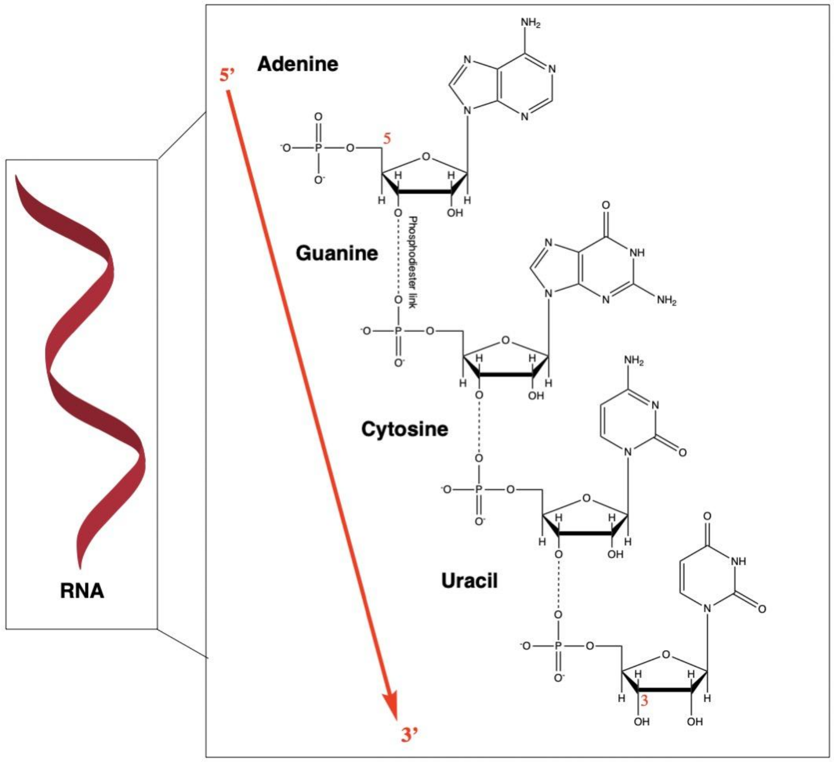


Figure 3-1. Molecular structure of RNA

4. DNA to RNA to Proteins

So we now know what the structures of DNA and RNA look like and how the chain of nucleotides are arranged in each polymer. But what's next? How does a DNA molecule actually transmit its genetic information to affect a human or other organism's features?

Recall the central dogma of molecular biology. The central dogma states that information flows from DNA → RNA → proteins. **Transcription** is the DNA → RNA part of the central dogma. It occurs in the nucleus. During transcription, a copy of **mRNA** (messenger RNA) is made that is complementary to a strand of DNA. mRNA is an intermediary molecule that carries information from DNA in the nucleus to ribosomes in the cytoplasm, where proteins are made. After transcription, an mRNA molecule is ready to initiate protein synthesis in the cytoplasm. This process is called **translation**. During translation, the nucleotide sequence of an mRNA molecule is translated into the amino acid sequence of a polypeptide with the help of **tRNA** (transfer RNA). However, because there are only four different types of nucleotides present in an mRNA molecule and 20 different types of amino acids in a protein, the sequence of nucleotides in the mRNA is read in groups of three. Each group of three consecutive nucleotides in RNA is called a **codon**, and each codon specifies either one amino acid or a stop to the translation process based on a set of rules called the **genetic code**.

Example #2. Complete the complementary mRNA strand for each given strand of DNA

a. ATGTCGCTGATACTGT

b. GGCATTCGCGATCATG

c. ACTAACGGTAGCTAGC

Example #3. Using the genetic code, translate the amino acid sequence of each given mRNA strand.

a. AUG CAC UGU CCU UUC GCU GAC

b. GAG AUC UGG UUG GAA UCG

c. AGC GUA UUA ACG UAU CAU

5. Creating DNA and RNA

Recap: genetic information carried in DNA is used to synthesize proteins through intermediary RNA molecules. Now it's time to switch gears and use Maestro to visualize the structures of DNA and RNA that we have learned so far.

<u>Computational Exercise:</u> Creating DNA and RNA strands in Maestro

This exercise involves four parts:

1) Create DNA and RNA structures using Build Biopolymer and visualize hydrogen bonding within the DNA and RNA
2) Compare and contrast the structures of DNA and RNA using Tile View
3) Visualize the overall shape of DNA using Surfaces
4) Measure the distance between base pairs in DNA

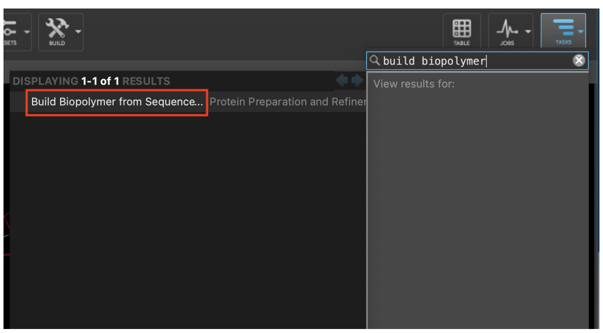


Figure 5-1. Opening Build Biopolymer.

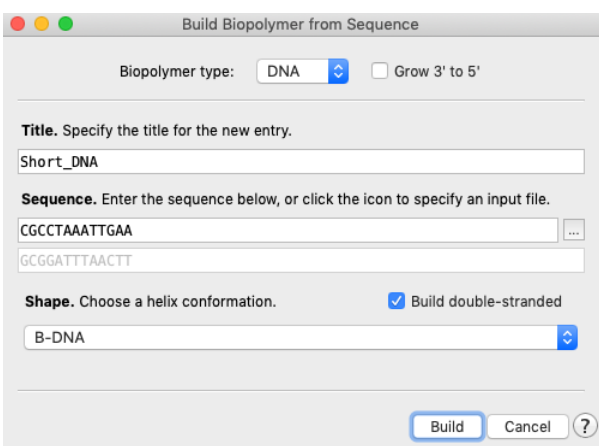


Figure 5-2. Input DNA Sequence into Build Biopolymer.

Part 1. Creating DNA and RNA using Build Biopolymer and visualizing H-bonding

1. Open the **Tasks Bar**
2. In the search bar, type "**Build Biopolymer from Sequence**"
3. Click on > **Build Biopolymer from Sequence**
4. Select > **DNA** as Biopolymer type from the dropdown menu
5. Name the molecule "**Short_DNA**"
6. Enter the Sequence > **CGCCTAAATTGAA**
    - Looking at the picture you can see that the sequence is automatically completed below in gray
    - **Reminder: Checkmark Build double-stranded**
7. Change the **Shape** > **B-DNA**
8. Click > **Build**

9. Go to the Workplace toggles in the bottom right hand corner and select the interactions toggle.
10. Select the “Non-Covalent bonds” (drop down) > **All**
11. Select the “Pi interactions” (drop down) > **All**

Pause here and zoom into the DNA molecule using your scroll wheel to get a closer look at the hydrogen bonds. *Remember, the Hydrogen Bonds appear as yellow dotted lines in the DNA structure.*

12. Open the **Tasks Bar**
13. In the search bar, type “**Build Biopolymer from Sequence**”
14. Click on > **Build Biopolymer from Sequence**
15. Select > **RNA** as Biopolymer type from the dropdown menu
16. Name the molecule “**Short_RNA**”
17. Enter the Sequence > **AUGAUCUCGUAA**
    - **Reminder: Toggle off Build double-stranded**
18. Click > **Build**
19. Select the “Non-Covalent bonds” (drop down) > **All**
20. Select the “Pi interactions” (drop down) > **All**

Pause here and zoom into the RNA molecule using your scroll wheel to get a closer look at the hydrogen bonds. *Remember, the Hydrogen Bonds appear as yellow dotted lines in the RNA structure.*

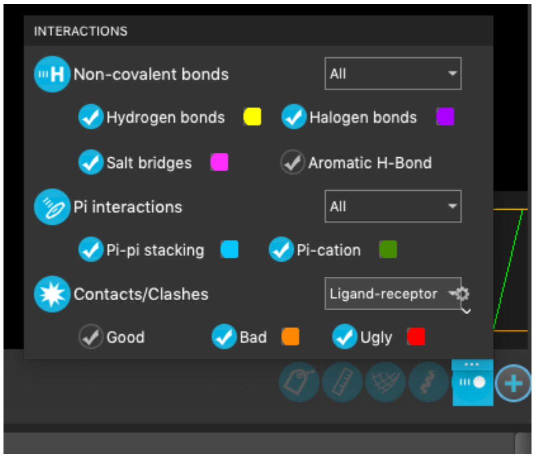


Figure 5-3. Opening Non-Covalent bonds.

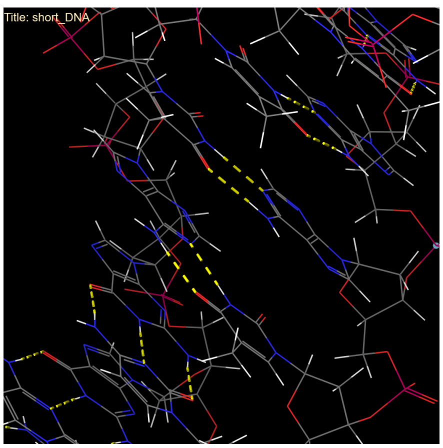


Figure 5-4. Visualizing hydrogen bonds in DNA.

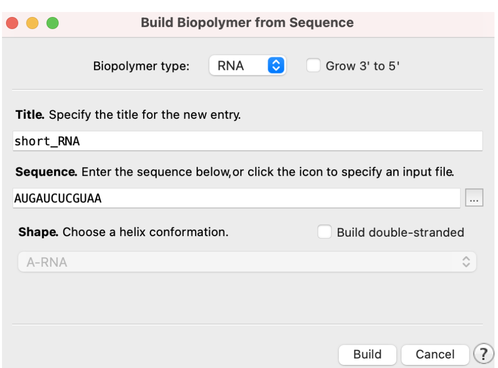


Figure 5-5. Input RNA Sequence into Build Biopolymer.

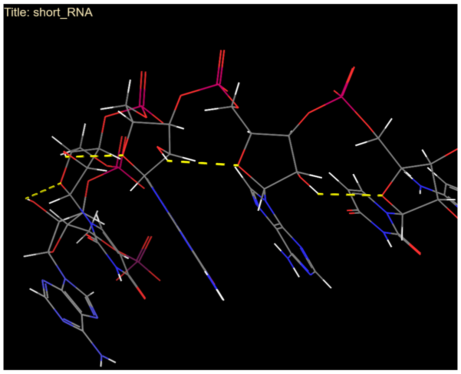


Figure 5-6. Visualizing hydrogen bonds in RNA.

Question #1: Roughly how many Hydrogen Bonds can you count in the DNA and RNA molecules? *Remember, the Hydrogen Bonds appear as yellow dotted lines on the Maestro interface.*

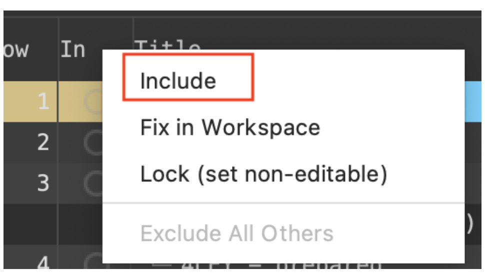


Figure 5-7. Including short_DNA and short_RNA in the workspace.

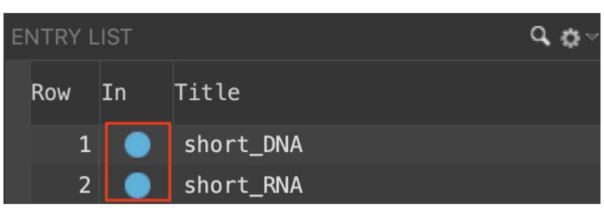


Figure 5-8. short_DNA and short_RNA have been included in the workspace.

Part 2. Compare and contrast the DNA and RNA molecules

21. Right click on > **short_DNA** in the project table
22. Click > **Include**
23. Right click on > **short_RNA** in the project table
24. Click > **Include**
    - When a structure has been included in the workspace, you will notice blue circles next to each entry list.
25. Click on the “plus sign” at the bottom-right of the Maestro interface
26. Click > **Tile by** > **Entry**

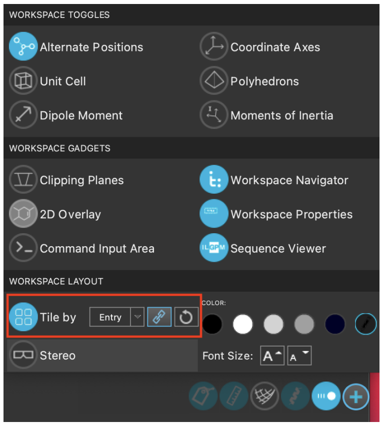


Figure 5-9. Toggle on Tile view.

Pause here and zoom in/out, rotate the DNA and RNA molecules. What similarities can you observe between the two structures? What differences are most noticeable?

Question #2: Take a screenshot of your short_DNA and short_RNA structures side-by-side in the tile view. Paste your screenshot in the table below. What are some similarities and differences you can observe between the DNA and RNA structures? Note them down in the table below.

DNA and RNA side-by-side screenshot:

Similarities	**Differences**

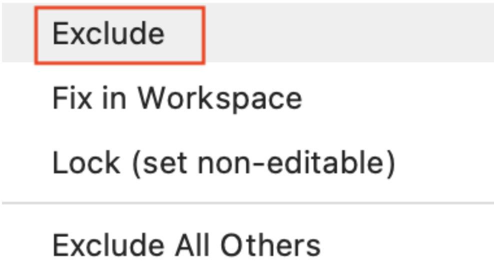


Figure 5-10. Excluding short_RNA from the workspace.

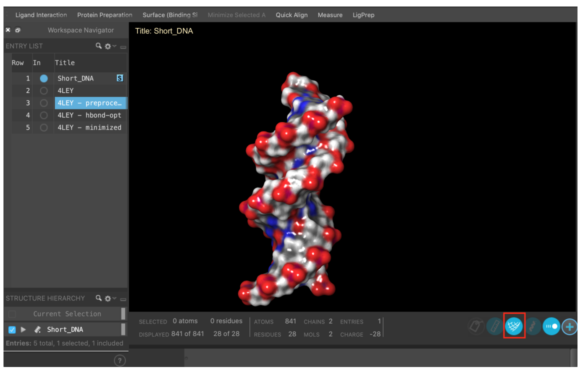


Figure 5-11. Adding a surface to the DNA structure.

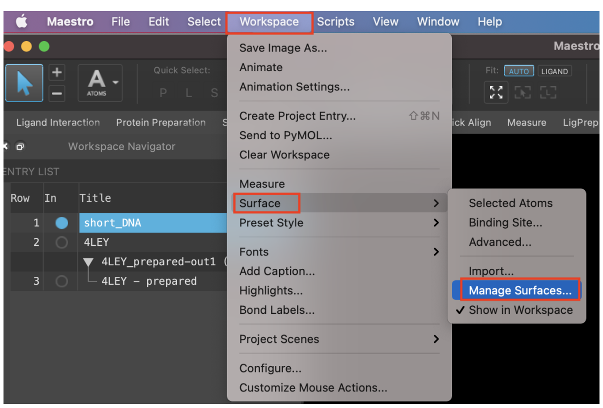


Figure 5-12. Opening the Manage Surfaces panel.

Part 3. Adding a surface to the DNA

27. Right click on > **short_RNA** in the project table
28. Click > **Exclude**
29. Click on the "plus sign" at the bottom-right of the Maestro interface
30. Toggle off Tile view
31. Click on the surface icon at the bottom-right of the Maestro interface to add a surface to the DNA molecule
32. Click on > **Workspace** > **Surface** > **Manage Surfaces** in the toolbar
33. Click on > **Display Options**
34. Keep **Style** > as **Solid**
35. Change the **Color Scheme** > **Other Property**
36. Then select **Residue Charge** and Click > **OK**

Learn more: Electrostatic surface potentials are colored red for negatively charged residues and blue for positively charged residues, while white/gray represents neutral residues. See the chemical bonding lesson for more information!

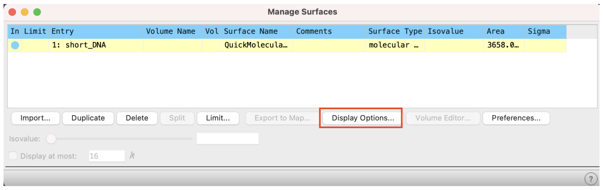


Figure 5-13. Opening Display Options.

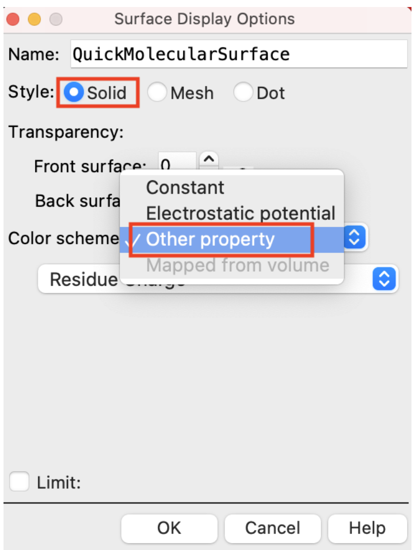


Figure 5-14. Changing the Color Scheme to Other Property.

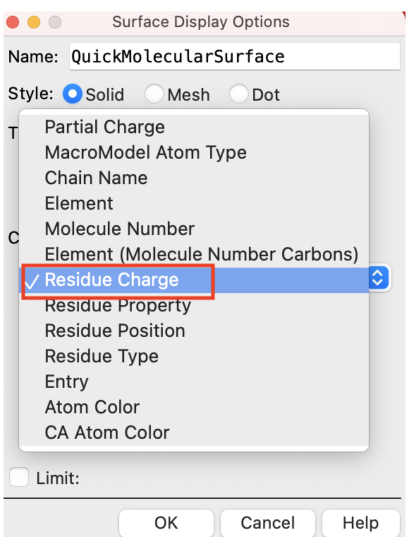


Figure 5-15. Selecting Residue Charge.

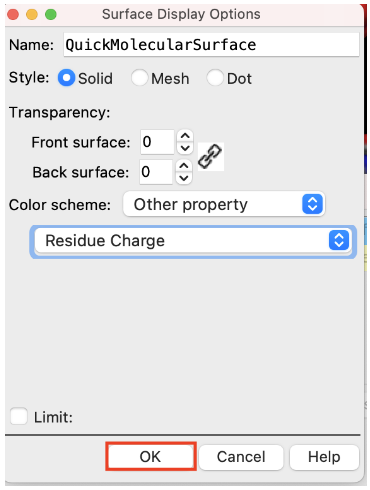


Figure 5-16. Click OK.

Question #3: Read the following two articles on [DNA]() and the [sugar-phosphate backbone](). Why is the sugar-phosphate backbone of DNA negatively charged? What function does this serve?

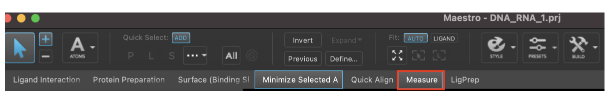
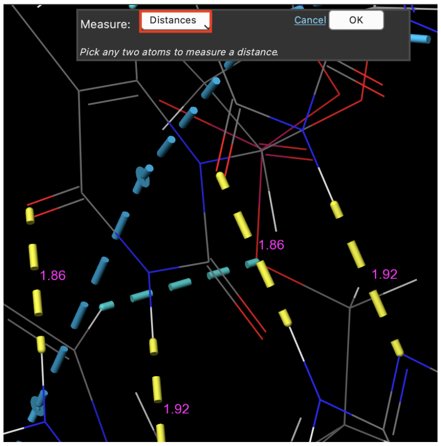


Figure 4-19. Click on Measure in Favorites Toolbar.

Part 4. Measuring distance between bases in the DNA

37. Toggle off the surface
    - To activate and deactivate surfaces, in the bottom-right hand corner there is a "Patch" icon. Click that icon to turn the surface on and off.
38. In your Favorites Toolbar click **Measure**
    - Keep the dropdown menu to **Distances**

 *Figure 4-20. Measuring distance of hydrogen bonds in each base pair.*	39. Measure the distance of the hydrogen bonds in each base pair ○ To measure the length, click the start of one of the bases and click to its matching base in the pair to see the distance between them 40. When you are finished click **OK**

Question #4: List what hydrogen bond distances (in units of Ångstroms) you see between the DNA base pairs.

Question #5: Other than hydrogen bonds, what are other non covalent interactions that you see within the DNA?

6. Individual Exercises

Part A: Calculate the distance between bases in your short_RNA structure. You can follow the same steps from Part 4 of the computational exercise.

1) List some of the hydrogen bond distances (in units of Angstroms) between the RNA bases. What do you notice about the hydrogen bond lengths in RNA?

2) What overall conclusion can you draw about hydrogen bond lengths in the structures of DNA and RNA?

Part B: Identifying base pairs in DNA.

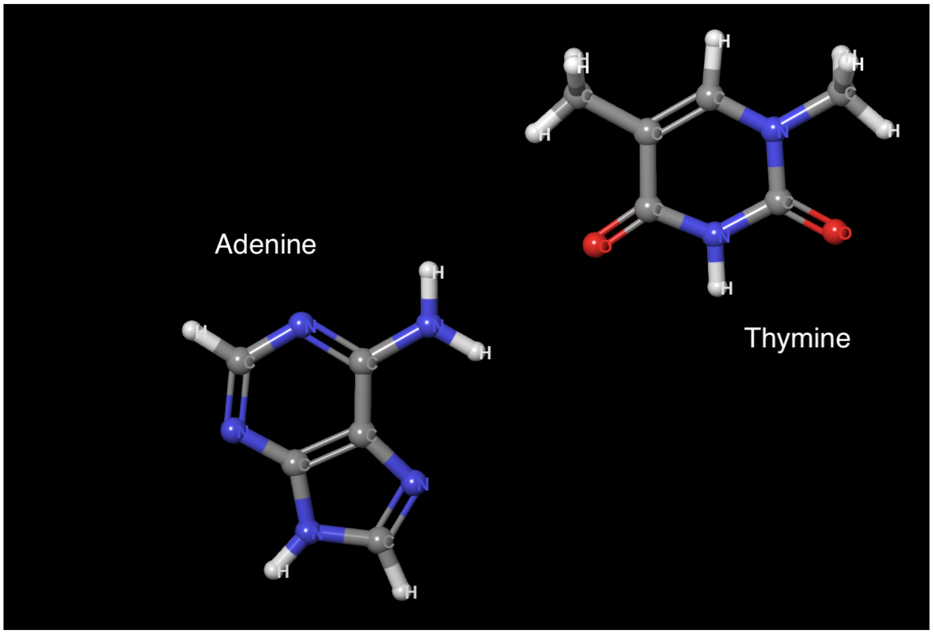
1) Zoom into your short_DNA structure and identify an instance where A is paired with T and where G is paired with C. Take screenshots of each base pair.

A - T screenshot:	**G - C screenshot:**

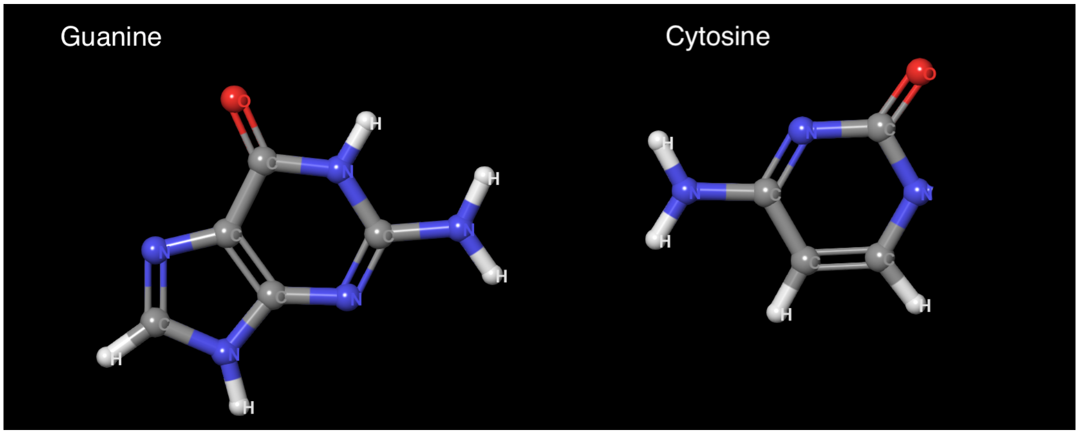
2) How did you identify which base pair was which?

Part C: Oxygen and nitrogen are electronegative atoms found in nitrogenous bases. They are represented in models by the color conventions: red for oxygen, and blue for nitrogen. Electronegative O and N atoms with free lone pairs are potential **hydrogen bond acceptors**. Hydrogen atoms attached to very electronegative atoms like O and N have strong partial positive charge and are potential **hydrogen bond donors**.

1) In the structures of adenine and thymine below, where are the hydrogen bond acceptors and donors? Draw an arrow pointing outwards to indicate a hydrogen bond donor, and draw an arrow pointing inwards to indicate a hydrogen bond acceptor.



2) In the structures of guanine and cytosine below, where are the hydrogen bond acceptors and donors? Draw an arrow pointing outwards to indicate a hydrogen bond donor, and draw an arrow pointing inwards to indicate a hydrogen bond acceptor.



7. Summary, Additional Resources, and References

In this lesson, students learned how to use the Biopolymer Builder to create a DNA and RNA molecule, visualize hydrogen bonding, measure distances within base pairs, as well as generate electrostatic potential surfaces of DNA. Using Maestro, students were able to interact with the DNA and RNA structures by using the graphical user interface to zoom in/out, measure bond lengths, and move around the molecules.

For further learning:

- https://proteopedia.org/wiki/index.php/DNA
- https://proteopedia.org/wiki/index.php/RNA
- From RNA to Protein
- Introduction to Computational Chemistry, 3rd Edition
- Essentials of Computational Chemistry: Theories and Models, 2nd Edition
- Molecular Modelling: Principles and Applications, 2nd Edition
- See the Build Biopolymer help documentation

8. Glossary of Terms

Entry List - a simplified view of the Project Table that allows you to perform basic operations such as selection and inclusion

Included - the entry is represented in the Workspace, the circle in the In column is blue

Project Table - displays the contents of a project and is also an interface for performing operations on selected entries, viewing properties, and organizing structures and data

Recent actions - This is a list of your recent actions, which you can use to reopen a panel, displayed below the Browse row. (Right-click to delete.)

Scratch Project - a temporary project in which work is not saved. Closing a scratch project removes all current work and begins a new scratch project

Selected - (1) the atoms are chosen in the Workspace. These atoms are referred to as "the selection" or "the atom selection". Workspace operations are performed on the selected atoms. (2) The entry is chosen in the Entry List (and Project Table) and the row for the entry is highlighted. Project operations are performed on all selected entries

Working Directory - the location that files are saved

Workspace - the 3D display area in the center of the main window, where molecular structures are displayed

Nucleic acid - one of the four major groups of biological macromolecules that make up life

DNA - a nucleic acid that carries genetic material found nearly in all living cells on earth

RNA - a single stranded nucleic acid that carries out the instructions coded in DNA

Base pairing - the principle by which nitrogenous bases in DNA bond with each other

Sugar-phosphate backbone - a polynucleotide chain linked by covalent bonds found in the structures of DNA and RNA