6.1 DNA and the Code of Life

When a child has the same colour hair or the same-shaped nose as one of his or her parents, it is said that there is a family resemblance. Throughout history, humans have had many ideas about what type of substance might be passed from parent to child that accounts for family resemblances. Before the exact molecule responsible for heredity was identified, Mendel and other scientists determined that genes, carried on chromosomes (**Figure 1**), control phenotypic characteristics. Chromosomes are passed from parents to offspring through gametes. In this way, the diversity of individuals, and indeed the diversity of all life, is a reflection of the different genes organisms inherit.

Figure 1 A human chromosome

nuclein the original name given to DNA when it was discovered in the nucleus of cells by Friedrich Miescher in 1869

The Discovery of DNA as Genetic Material

Modern science has shown that deoxyribonucleic acid (DNA) is the molecule that stores and transmits genetic information from parents to offspring. Many scientists have contributed to the discovery of the hereditary molecule DNA.

The story began in 1869 when Friedrich Miescher, a Swiss scientist, investigated a compound found in the nucleus of the cells he studied; Miescher called this compound **nuclein** (now known as DNA). After Miescher's discovery, numerous scientists conducted experiments in an attempt to determine if nuclein was the material that stored and passed on genetic information. The chemical components of nuclein were discovered in the 1920s, but it took decades of research before it was proven that DNA is responsible for heredity.

In the 1930s, Danish biologist Joachim Hammerling verified that genetic material was contained in the nucleus. Hammerling's experiments involved large, green, single-celled algae called *Acetabularia* that have three distinct regions: a foot, a stalk, and a cap. Using a microscope, he saw that the foot contained the nucleus. In his first experiment, he cut off the cap of several algal cells, and the algae were able to regenerate new caps. In the second experiment, he cut off the foot, but this time none of the algal cell regenerated (**Figure 2**). Therefore, he reasoned, the material that was directing new growth must be located in the nucleus, found in the foot. Hammerling could not verify what the genetic material was, only that it was found in the nucleus. This experiment was a vital step in the study of genetics.

WEB **LINK**

To learn more about the discovery of DNA,

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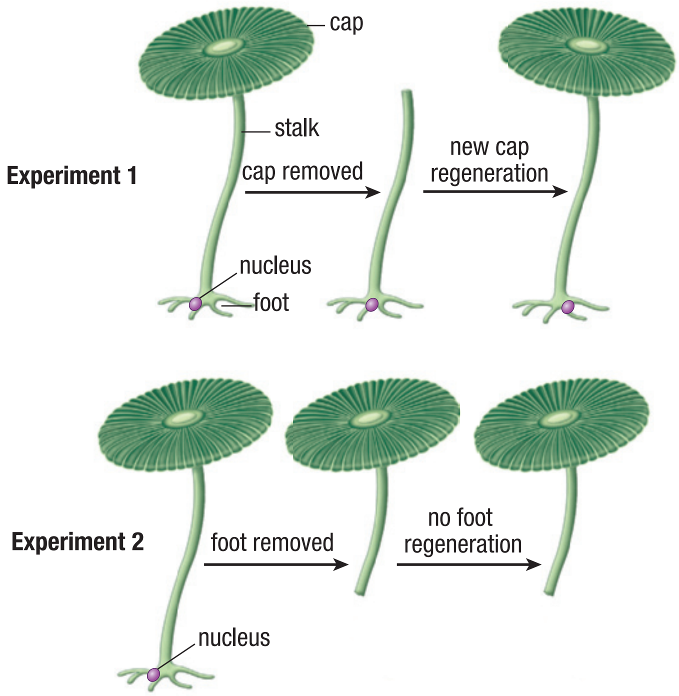

Figure 2 Since a new cap grew only from an existing foot that contained the nucleus, Hammerling concluded that the nucleus must contain the hereditary material.

At this point, scientists hypothesized that DNA was the hereditary material. However, the hypothesis was not proven until 1952, when Alfred Hershey and Martha Chase conducted experiments using a bacterial virus. Bacterial viruses invade bacterial cells and then use the organelles found in the bacteria to produce more bacterial viruses. Hershey and Chase showed that the viruses needed only to inject their DNA into the bacteria to produce more bacterial viruses. They concluded that DNA directed the production of new viruses and that DNA was the hereditary material.

Although Hershey and Chase worked only with bacteria, they realized that the idea could be applied to all organisms. Their discovery confirmed the work done by Hammerling, who had concluded that hereditary material is located in the nucleus.

The Chemical Composition of DNA

In the 1920s, Phoebus Levene discovered that DNA had three main components:

- a pentose sugar (a cyclic, 5-carbon sugar)
- a phosphate group that has a negative charge
- a nitrogenous base

Together, the three components are called a **nucleotide**. About 3 billion pairs of nucleotides make up the human genome. There are four possible bases for the nucleotides of DNA: adenine (A), guanine (G), thymine (T), and cytosine (C) (**Figure 3**).

nucleotide the repeating unit in DNA; it comprises a deoxyribose sugar, a phosphate group, and one of the four nitrogenous bases

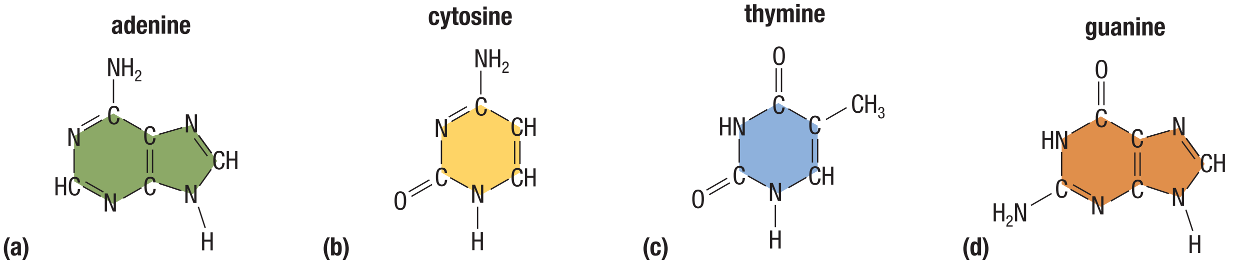

Figure 3 The four nitrogenous bases, A, C, T, and G, in DNA

In 1940, Erwin Chargaff discovered a key relationship among the nitrogenous bases in DNA:

- The amount of adenine (A) is always equal to the amount of thymine (T).
- The amount of guanine (G) is always equal to the amount of cytosine (C).

Figure 4 shows a nucleotide, comprising a phosphate group, a pentose sugar, and a nitrogenous base. Notice from the figure that DNA has a negative charge because of the phosphate ions in its chemical backbone.

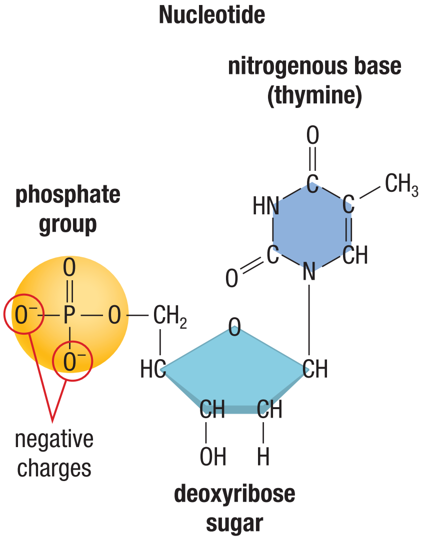

Figure 4 The three main components of DNA are shown here (with thymine as the nitrogenous base).

The Structure of the DNA Molecule

Scientists had now gathered a great deal of information about the chemical composition of DNA, but they were still missing a few pieces of the puzzle. To understand how DNA stores and transmits genetic information, scientists needed to establish the precise structure of the molecule.

X-ray crystallography a technique in which a pure substance is subjected to X-rays; the pattern in which the X-rays bend and spread helps reveal the structure of the pure substance

In 1951, researcher Rosalind Franklin began to study DNA using **X-ray crystallography.** Working together with another scientist, Maurice Wilkins, Franklin determined that DNA molecules form a helix, or corkscrew, shape (**Figure 5**).

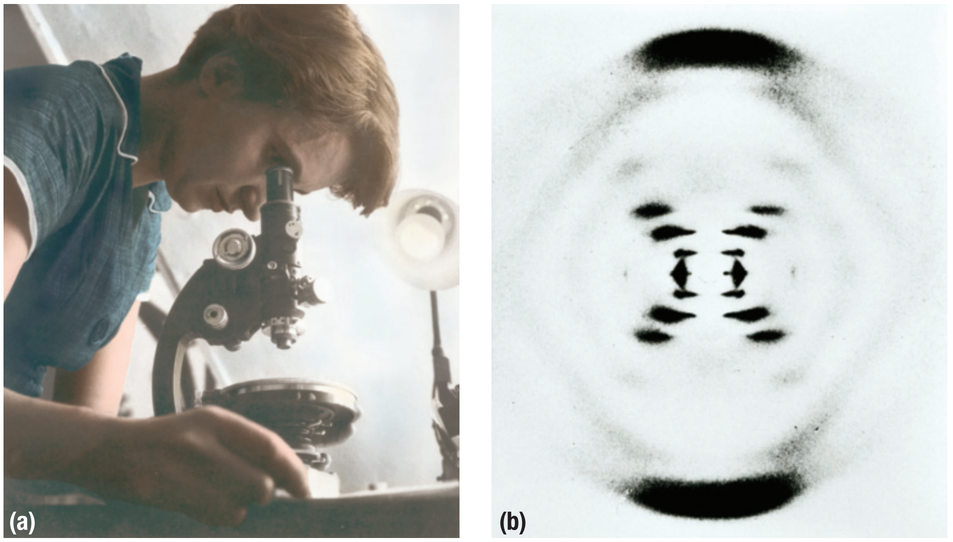

Figure 5 (a) Rosalind Franklin used X-ray crystallography to reveal the helical structure of DNA. In this technique, a crystal of DNA is exposed to X-rays in order to produce (b) a diffraction pattern. The diffraction pattern can then be used in an effort to reconstruct the positions of the atoms in the molecules of DNA.

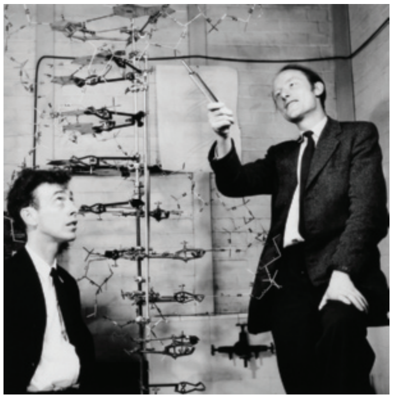

Figure 6 James Watson and Francis Crick with their model of a DNA molecule, which integrated all of the chemical information that was known about DNA at the time

In 1953, James Watson and Francis Crick, two scientists at Cambridge University, met with Wilkins, who shared the information he and Franklin had discovered. Using what they knew about the chemical structure of DNA, Watson and Crick built a model of DNA. Watson and Crick's model showed the molecular structure of DNA to be a double helix (**Figure 6**). This model was based on a single X-ray diffraction image that Franklin had taken, as well as on other chemical information about DNA that was known at the time. Their model accounted for the following information, discovered and shared by other scientists:

1. DNA is made of a pentose sugar, a phosphate group, and one of four nitrogenous bases (Levene, 1920s).
2. The proportion of adenine (A) to thymine (T) is equal. The proportion of cytosine (C) to guanine (G) is equal (Chargaff, 1940).
3. DNA has the shape of a helix or corkscrew (Franklin and Wilkins, 1951).

Watson and Crick used this information to put together all the "puzzle pieces" provided by their peers when creating their molecular model of DNA. Franklin's X-ray images of DNA crystals were of the highest quality, and were instrumental in Watson and Crick's final determination of the structure of DNA (now widely accepted as being accurate).

A Model for DNA

scientific model a simplified representation of a concept; can be tangible or conceptual

A **scientific model** can be a representation of a system or a concept. Watson and Crick built on the work of the scientists before them to create their model of DNA. Using this information, they proposed that DNA is made up of two strands of repeating DNA nucleotides that run in opposite directions.

The chemical backbone of a DNA strand is made up of alternating phosphate groups and pentose sugars. Attached to this backbone are nitrogenous bases: adenine, guanine, cytosine, and thymine (**Figure 7**). The bases of one strand are paired with the bases of the other strand in the following arrangement:

- Thymine (T) is always bonded to adenine (A).
- Cytosine (C) is always bonded to guanine (G).

This type of pairing is known as **complementary base pairing**. Watson and Crick proposed a complementary base-pairing molecule in order to explain Chargaff's observations of equal proportions of bases.

complementary base pairing pairing of the nitrogenous base of one strand of DNA with the nitrogenous base of another strand; adenine (A) pairs with thymine (T), and guanine (G) pairs with cytosine (C)

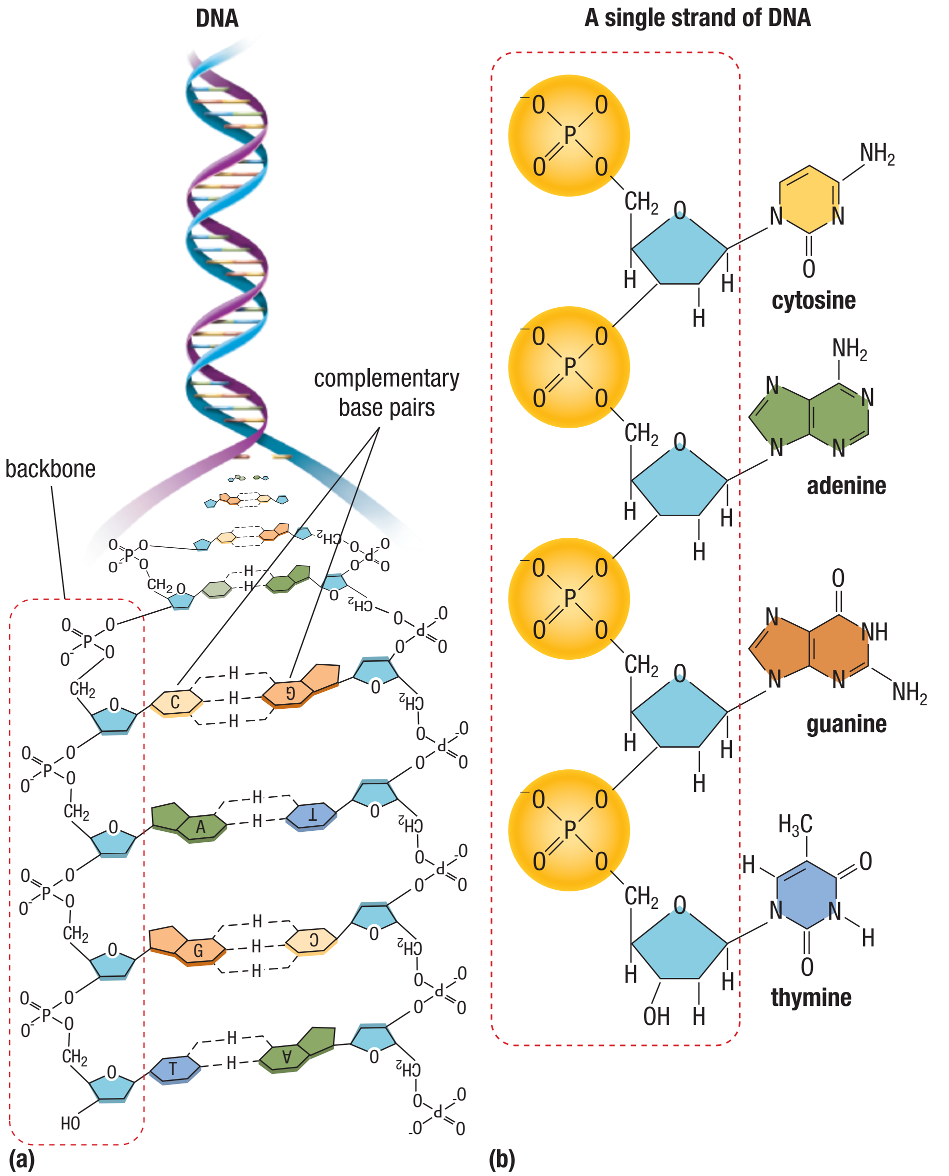

Figure 7 DNA is double stranded. The outer backbone consists of alternating pentose sugar and phosphate groups. The inner part of the molecule contains the complementary bases.

Since the bases are complementary, there is no need to know the nucleotide base sequence for both strands. Once the nucleotide base sequence is determined for one strand, the sequence on the complementary strand can be determined easily. For example, the complementary base sequence for ATGGCCATC would be TACCGGTAG. **Figure 8** shows more examples.

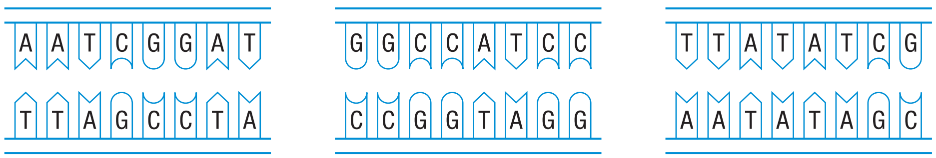

Figure 8 Examples of complementary base pairing. T always pairs with A and G always pairs with C.

LEARNING TIP

DNA Twist
DNA exists as a right-handed double helix as well as a left-handed double helix. The two types of helix are mirror images of each other. Watson and Crick built a model of a right-handed helix.

Mini Investigation

Origami DNA

Skills: Performing, Observing, Analyzing, Evaluating, Communicating — SKILLS HANDBOOK A2.1

Scientists build models to better understand a concept. Watson and Crick used information about the chemical composition of DNA to build a model of DNA. Once the structure was determined, the chemical mechanisms of processes involving DNA, such as chromosome replication, could be further investigated.

In this activity, you will build a model of DNA using the ancient Japanese art of origami (paper folding). There are two types of folds: mountain folds and valley folds. In mountain fold, the crease is toward you (**Figure 9(a)**). In a valley fold, the crease is away from you (**Figure 9(b)**).

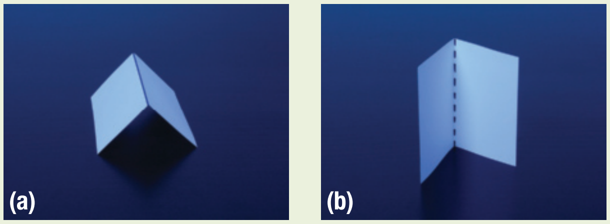

Figure 9 (a) A mountain fold (b) A valley fold

Equipment and Materials: scissors; ruler; DNA origami handout

1. Cut around the blank trim on your handout.
2. Make mountain folds for all of the solid vertical lines down the page. Make valley folds for all of the dashed vertical lines down the page (**Figure 10**).
3. Bring the two sides of the model together.
4. Hold the model so that the side labelled "front" is facing you. Fold the two sides of the DNA model so that the front side is flat (**Figure 11**).

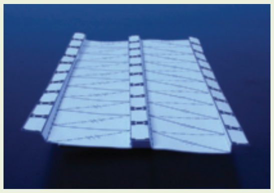

Figure 10

Figure 11

5. Make a mountain fold for each solid horizontal line on the front side (**Figure 12**).
6. Flip the model so that the side labelled "back" is facing you. Make a mountain fold for each solid diagonal line on this side (**Figure 13**).

Figure 12 Folded horizontal lines

Figure 13 Folded diagonal lines

7. Fold all the creases together in the directions of the folds made in Steps 5 and 6. The model should fold up like an accordion. As you are folding, pinch the middle of the model to keep it together to make a cylindrical (or helical) shape as in **Figure 14**.
8. Release the model. Straighten out the sides of the model (the DNA backbone) so that the sides are perpendicular to the creases made in Steps 5 and 6. Your model should have a helical shape (**Figure 15**).

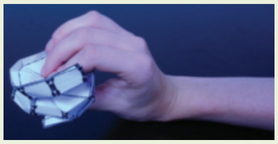

Figure 14 When you complete the folding, you will be able to hold the model in one hand.

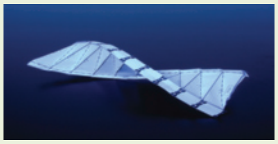

Figure 15

A. Compare your model to the known structure of DNA. How does it compare? T/I

B. Identify the backbone and the nitrogenous bases in your model. T/I

C. The human genome has 3 billion base pairs. There is a turn every 10 nucleotides, a distance of 3.4 nm. Measure the distance of 10 nucleotides on your model. By what factor does your model have to be reduced to attain the actual size of the DNA molecule? T/I

D. How long would your paper model have to be in order to represent 3 billion base pairs? T/I

6.1 Summary

- Deoxyribonucleic acid (DNA) stores and transmits genetic information from parent to offspring.
- DNA is made up of repeating nucleotides. Each nucleotide consists of a sugar, a phosphate group, and a nitrogenous base.
- DNA has four nitrogenous bases: thymine (T), cytosine (C), adenine (A), and guanine (G).
- Thymine (T) and adenine (A) are complementary bases. Guanine (G) and cytosine (C) are complementary bases.
- James Watson and Francis Crick determined the structure of DNA. DNA consists of two strands that run in opposite directions. Each strand is made up of alternating phosphate and sugar molecules with nitrogenous bases attached to the backbone.

6.1 Questions

1. Outline the contributions of the following scientists in the determination that DNA is the hereditary material: K/U
   (a) Joachim Hammerling
   (b) Alfred Hershey and Martha Chase
2. What does DNA stand for? What are the three main components of DNA? K/U
3. Identify and explain Chargaff's contribution to the determination of DNA structure. K/U A
4. What is the complementary strand of TTGACAGTAAAA? A
5. Describe Watson and Crick's model of DNA. How does it account for all the experimental evidence about DNA composition that was known at the time? K/U C
6. Rosalind Franklin's work was key to understanding the structure of DNA. Conduct online research to learn more about her scientific accomplishments.
   (a) Describe her contributions to the understanding of DNA and viruses.
   (b) Why was she not nominated for the Nobel Prize in 1962?
   (c) Do you think she deserved more recognition than she received? Why or why not? T/I C A
7. Pick two of the experiments that were described in this section. For each one, identify the following.
   (a) What were the controlled and responding variables?
   (b) What hypothesis did the researchers use?
   (c) How did the researchers build up the evidence to draw their conclusion? K/U T/I A

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