Interactive Biology Multimedia Courseware

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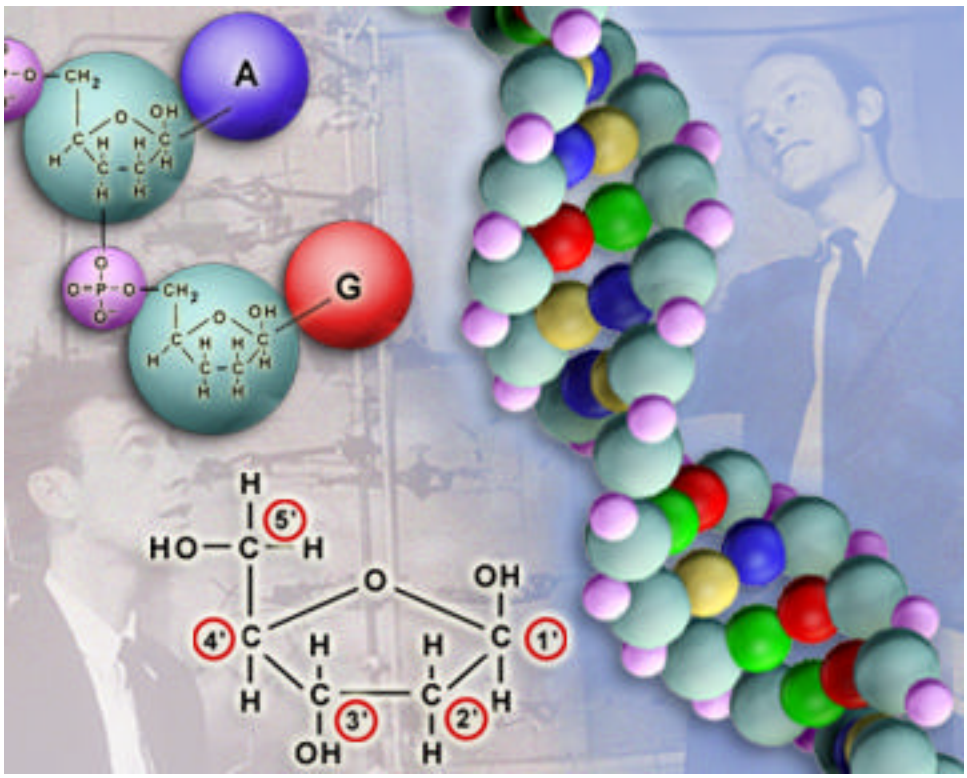
DNA: The Molecule of Life 2.0
Program Supplement



DNA: The Molecule of Life
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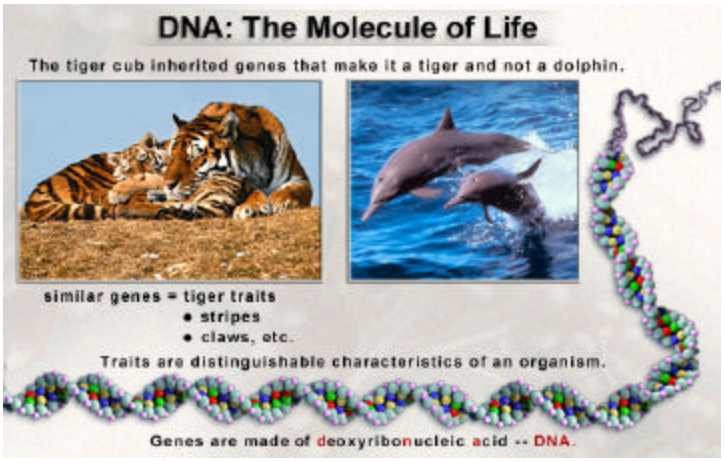
Scenes 1-10
Introduction and the Search for Heredity

Scene 1:



This tiger cub resembles its parents and other tigers, yet it is very different from this dolphin. Why? The answer lies in its **genes**. The cub inherited genes that make it closely resemble its parents and give it the characteristics, or **traits**, that make it a tiger and not a dolphin. Today, we know that genes are made of a substance called **deoxyribonucleic acid**, or DNA. However, it has only been since the middle of the 1900s that scientists have known the structure and function of DNA as the essential hereditary substance. This program will teach you about DNA, the substance that functions as genes and carries the information that made this young cub a tiger, like its parents.

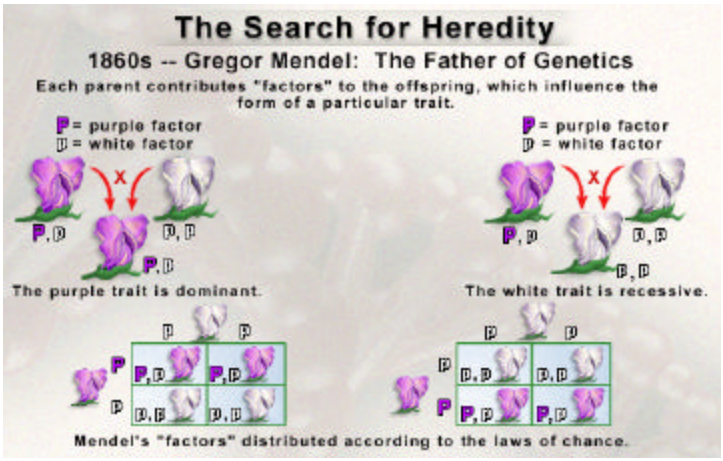
Scene 2:

DNA really is the molecule of life; it's life's information system. In addition to influencing how an organism looks and behaves, DNA tells cells how to grow, interact with other cells, and produce essential life-sustaining molecules. DNA is so important to life that nothing on Earth is considered alive unless it possesses DNA. In this program, you will examine historical experiments that provided clues to DNA's function as the carrier of hereditary information, and you will learn about steps that led to the discovery of DNA's chemical structure. In addition, you will learn how DNA is duplicated and repaired before being transferred to new living cells. The discovery of DNA is a history of scientific achievement and demonstrates our capacity for deduction through the scientific process.

Scene 3:

Heredity, which is the transfer of characteristics, or **traits**, from parent to offspring, is not a new concept. Stone tablets have been found that suggest ancient Babylonians created **pedigrees** to document traits champion horses passed to their offspring. However, nobody knew how or why such traits passed from generation to generation. People suspected something in blood carried traits; hence the term "pure bloodline" came to existence. Over two thousand years ago, the Greek philosopher Aristotle suggested only males passed hereditary traits to their children; whereas others believed the female solely determined an offspring's traits. Eventually, the belief that a child inherited traits representing a blend of its parents' traits came to dominate thoughts on heredity.

Scene 4:



Little occurred in the study of heredity until a period of rapid scientific advances in the latter half of the 1800s. In the 1860s, **Gregor Mendel** (1822-1884), who eventually came to be known as "the father of genetics," performed his famous experiments on pea plants. Mendel found that each parent contributed something he called "factors" to the offspring. Individual "factors" influenced the form of a particular trait. Traits were not simply a blend of the parents' characteristics. Sometimes a trait was dominant; that is, the trait was seen in the offspring even if just one parent had the trait. He observed dominant traits in purple pea flowers. Sometimes a trait was recessive, as he observed with white pea flowers. For recessive traits to appear, the offspring must inherit a recessive factor from both parents. These 'factors,' as Mendel described them, were divided up and distributed to offspring independently, according to the laws of chance.

Scene 5:

The next step toward discovering the substance of heredity came in 1869, from a biochemistry student named **Frederick Meischer**. While studying white blood cells isolated from pus-filled bandages, he discovered that treating the cells with **acid** would dissolve most of the cellular contents, leaving only the **nucleus**. If he treated the nucleus with **alkali**, and then acid, it yielded a grayish substance he called **nuclein**. Later, others found that subjecting the nucleus to stains and dyes produced dark bands, which they called **chromatin** — a term derived from Latin, meaning colored threads. Similar results were observed by treating chromatin as Meischer had treated the nucleus, and the researchers concluded that nuclein resided within bands of chromatin.

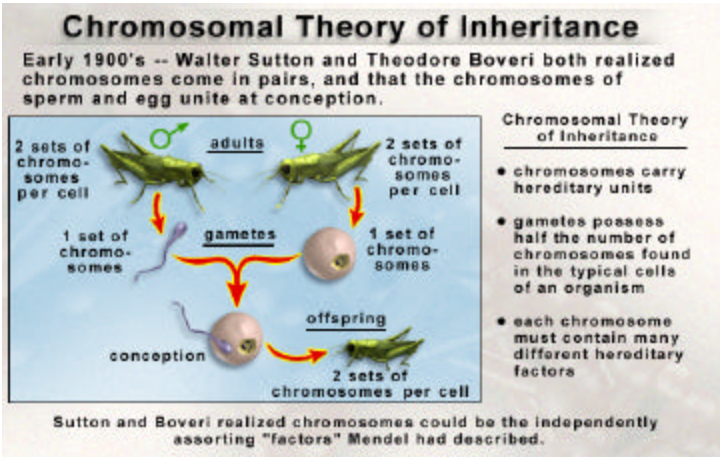
Scene 6:

Further research on chromatin found it contained large amounts of the elements Carbon, Hydrogen, Oxygen, Nitrogen, and Phosphorus; and it was acidic. The term "nuclein" coined by Meischer was replaced by nucleic acid, and shortly thereafter, two types of nucleic acid were discovered: deoxyribonucleic acid, or DNA, found mainly in the nucleus, and **ribonucleic acid**, or RNA, found mainly in the **cytoplasm** of the cell. At this point, scientists did not know the role chromatin and the nucleic acids played in the cell.

Scene 7:

In the 1880s, researchers observed that chromatin condenses into dense, darkly staining structures before cell division. These structures were given the name **chromosomes**, which literally means "colored bodies." Two different types of cell division were observed, and in both, the chromosomes duplicate before being distributed to new cells. In one type of cell division, duplicated chromosomes divide equally into two daughter cells. This was called **mitosis**. The other type form of cell division occurred in the production of gametes, or sex cells, such as the male's sperm or the female's **eggs**. In this type form , the chromosomes duplicate once, but two different cell divisions occur, yielding four new cells with exactly half as many chromosomes as the original cell. This type form , in which the chromosome number is reduced after division, was called reduction division and later termed **meiosis**.

Scene 8:



In the early 1900s, **Walter Sutton** (1877-1916) and **Theodore Boveri** (1862-1915) independently studied gamete formation. They both realized that an organism's chromosomes exist in pairs, but the sperm and egg have only one set of chromosomes. When the sperm and egg join at conception, they both contribute chromosomes so that the new organism created has a paired set of chromosomes. This led to the "chromosomal theory of inheritance," which surmised that chromosomes carry hereditary units, and that the sperm and egg that unite at conception each have half the number of chromosomes found in the typical cells of the resulting offspring. Sutton and Boveri realized that the chromosomes inherited from the father's sperm and the mother' s egg could be the independently assorting "factors" Mendel described. Since humans have thousands of different traits, but only 46 chromosomes in their cells, Sutton surmised that each chromosome must contain many different hereditary factors, or genes.

Scene 9:

The famous geneticist, **Thomas Hunt Morgan** (1866-1945), supported the Chromosomal Theory of Inheritance with his pioneering work on fruit flies. Fruit flies have only four pairs of chromosomes and reproduce rapidly. Therefore, they make ideal subjects for the study of heredity, also known as genetics. Male fruit flies, like human males, have both an X and a Y chromosome whereas females have two X-chromosomes. He found that certain genes resulted in traits

in males that did not follow Mendel's dominant and recessive inheritance patterns. Morgan realized that since males have only a single X-chromosome, they have just a single copy of the gene, and therefore, there could be no dominant or recessive pattern. This observation aided him in showing that a particular gene could be traced to a specific chromosome. In further studies, he found that genes for certain traits were arranged in a specific order along chromosomes.

Scene 10:

To recap what you've learned — by this point in time, researchers determined that parents contribute hereditary information to their offspring. This hereditary information was found in the chromosomes of the sperm and egg, which unite at fertilization to create a new organism. Chromosomes clearly carried hereditary information in the form of genes, but researchers were uncertain which component of chromosomes acted as genes. Chromosomes were known to contain the nucleic acid, DNA, and further research showed chromosomes also contained **protein**. The next step in finding how chromosomes functioned as genes involved determining whether DNA or protein carried the hereditary information. Many researchers suspected that protein acted as genes because they thought DNA would be too simple of a molecule to code for the diversity of traits found in living organisms. In the 1920s, a chemist named **Phoebus Aaron Levene** (1869-1940) performed experiments that described the chemical makeup of DNA. This furthered the belief that DNA was a simple molecule.

Scenes 11-24
Determining DNA Composition and Its Role in Heredity

Scene Number

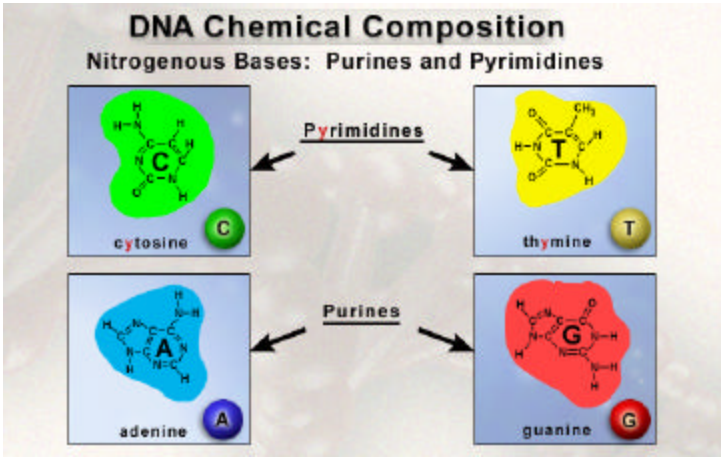
V. DNA Chemical Composition
    A. P.A. Levene Identifies DNA Components
        1. DNA is Composed of Sugars, Phosphate Groups and Nitrogenous Bases (11)
        2. Pyrimidines: Cytosine and Thymine, and Purimes: Adenine and Guanine (12)
        3. The Nucleotide
            a. Labeling Carbon Atoms Help Describe How Nucleotides Link Together (13,14)
            b. Is DNA or Protein the Hereditary Molecule? (15)

VI. Experiments Leading to the Discovery of DNA as the Hereditary (Genetic) Molecule
    A. Frederick Griffith's Pneumococcus Experiment
        1. Unexpected Result (16,17)
        2. The Transfer of Genetic Material—Transformation (18)
    B. Avery, MacLeod, McCarty Cell Extract Experiment
        1. Identification of DNA as Hereditary Material (19)
        2. Science Remained Skeptical—Protein or DNA? (20)
    C. Chargaff Finds the Same Four Nucleotides in All Organisms
        1. Chargaff's Rules (21)
    D. Hershey and Chase Bacteriophage Experiment (22)
        1. Experimental Design (23)
        2. DNA Shown to be Genetic Material (24)

Scene 11:

Levene found that DNA consists of just three different units: sugar molecules, phosphate groups, and nitrogen rich bases. These molecules are comprised of the same chemical constituents researchers had earlier found in chromatin. The sugar molecules, called **deoxyribose**, are made of carbon, hydrogen, and oxygen arranged in a ring-like structure. The **phosphate groups** consist of a phosphorous atom surrounded by four oxygen atoms. The nitrogen rich, or **nitrogenous**, bases are the only molecules showing diversity in DNA; there are two types, purines and pyrimidines.

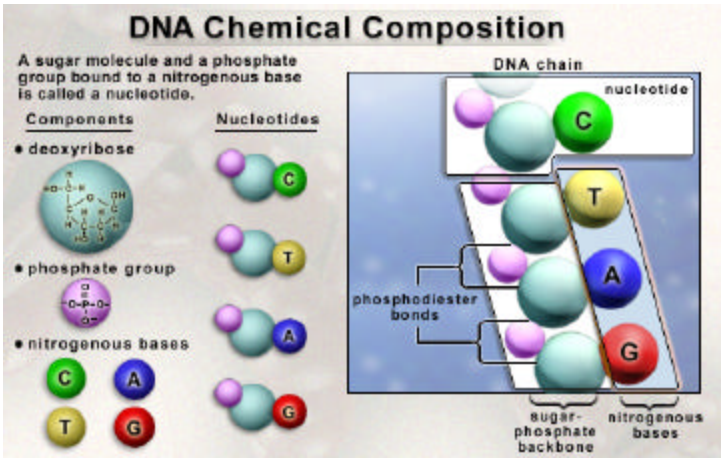
Scene 12:



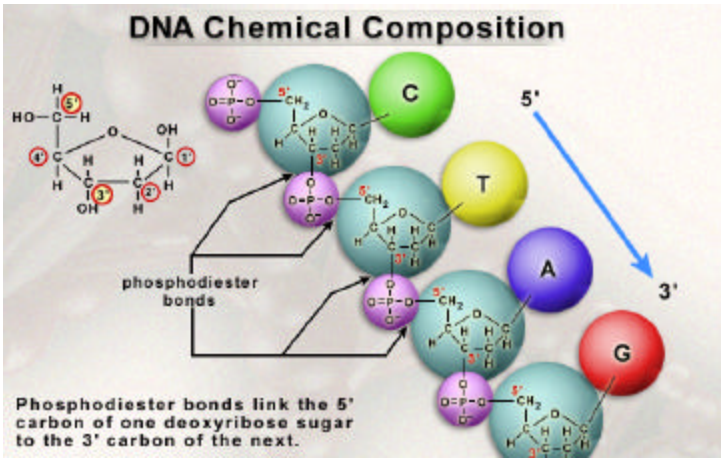
The type of nitrogenous bases called **pyrimidines**, are six membered rings made of carbon, nitrogen, hydrogen, and oxygen. The other type of nitrogenous bases, called **purines**, consists of five membered rings attached to pyrimidine type of rings. The two DNA pyrimidines are named **cytosine** and **thymine**, and the two purines are **adenine** and **guanine**. These bases are commonly abbreviated as C, T, A, and G. Also, it helps to remember which nitrogenous bases are pyrimidines if you note that thymine and cytosine are spelled with a "Y," and so is pyrimidine.

Scene 13:

Levene also discovered one phosphate group and one deoxyribose sugar molecule associate with each nitrogenous base in DNA, creating a structure known as a **nucleotide**. Since four nitrogenous bases exist in DNA, there are four different nucleotides. Later, Levene found that the nucleotides in DNA link together at specific places by what is known as a **phosphodiester** bond. The nucleotides essentially link together like a chain.



Scene 14:



You will notice that many atoms make up the molecules in DNA, and the structures could quickly become confusing. For these reasons, chemists number the carbons of the sugar molecules. This helps to describe molecules and discuss where specific bonds form. For instance the DNA sugar, **deoxyribose**, is easily distinguished from the RNA sugar, **ribose**, because deoxyribose lacks an oxygen atom at the number two position in the ring. The phosphodiester bonds Levene described occur when a phosphate group links sugar molecules together between the 5' (pronounced “5 prime”) carbon on one sugar, and the 3' (pronounced “3 prime”) carbon on the next deoxyribose sugar molecule. Because all of the nucleotides are linked together in this manner, molecular biologists would refer to this DNA chain as being oriented in a 5' to 3' direction.

Scene 15:

Although Levene identified the individual components of DNA and the manner in which nucleotides link together, the larger structure these "chains of molecules" assembled into remained unknown. Since DNA consists of only four different nucleotides, researchers believed it to be a very simple molecule and felt the nucleotides probably existed in equal amounts as a series of repeating units. Unfortunately, knowing the components of DNA did not solve the mystery of whether the DNA or protein component of chromosomes functioned as genes. The next steps in identifying the hereditary molecule involved determining exactly which component carried genetic information.

Scene 16:

In 1928, a researcher named **Frederick Griffith** unexpectedly set the groundwork for identifying the hereditary material during experiments he hoped would lead to development of a **vaccine** against **pneumococcus**, a bacterium that causes pneumonia. Griffith worked with two types of pneumococci. One type caused a severe form of pneumonia and was named the smooth strain because it made large smooth colonies. The other type did not cause disease and made small rough colonies; therefore, it was called the rough strain. Quite by accident, he discovered that some substance inside the cell could transform one strain of bacterium into the other if the two strains were mixed together.

Scene 17:

When Griffith injected mice with live, rough strain pneumococci, no disease resulted, and the mice survived as suspected. When mice were injected with the smooth, disease-causing strain, they died of pneumonia. When Griffith killed the smooth strain bacteria with heat, and then injected them into mice, no disease resulted and the mice lived. The unexpected result occurred when he mixed heat-killed, smooth bacteria with live, rough bacteria and injected this mixture into mice. Instead of observing living mice as expected, the mice all died. Griffith then examined the dead mice and found living, smooth strain bacteria.

Scene 18:

Griffith's unexpected result led him to suspect that genetic material responsible for giving the smooth strain bacteria its disease-causing characteristics had passed from the dead smooth strain bacteria to live rough strain bacteria, transforming them into a smooth strain. The heat had killed the original smooth bacteria, but obviously, the genetic material remained intact enough to transform the rough strain to smooth strain bacteria. Furthermore, this genetic change, which Griffith called **transformation**, was permanent. When Griffith isolated the transformed bacteria from dead mice and grew them in the lab, they continued to produce smooth colonies. Griffith discovered that genetic material can be transferred, but he did not know which substance acted as genetic material. A series of related experiments soon provided the answer.

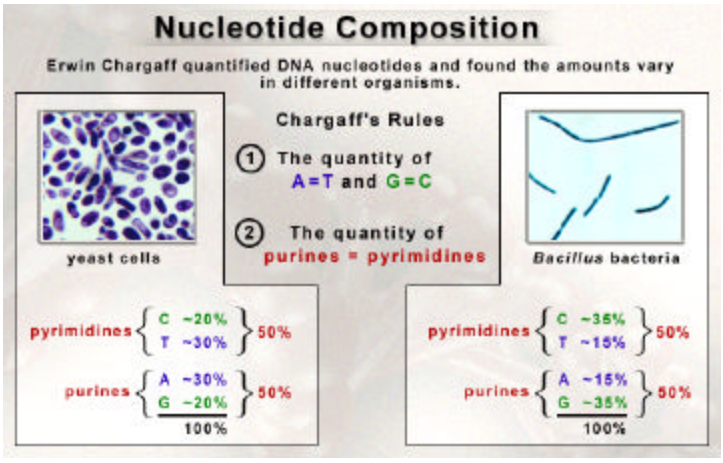
Scene 19:

Griffith's transformation experiment excited a researcher named **Oswald Avery,** who set out to identify which cellular component could change the genetic makeup of another organism. After about a decade of attempts, in 1944 Avery and his colleagues, **Colin MacLeod** and **Maclyn McCarty** published results of an experiment that identified DNA as the hereditary material. The team of scientists purified various substances from heat killed, smooth strain pneumococci and tested to see which substance could transform live, rough strain bacteria to smooth strain. They tested proteins, fatty substances called lipids, sugar based molecules called carbohydrates, and RNA — all without success. When they finally tested the stringy substance called DNA, cells were transformed, and they were sure DNA carried genetic information.

Scene 20:

Although Avery and colleagues had demonstrated DNA was genetic material, many scientists remained skeptical. Some researchers thought protein had contaminated the DNA, and was actually the genetic material. Others doubted that the genetic material of bacteria could be the same as that of more complex organisms such as plants and animals. DNA, containing its four different nucleotides of sugar, phosphate, and nitrogenous bases, was still widely held as being a simple molecule composed of repeating units. However, this did not deter a young chemist named **Erwin Chargaff** from attempting to quantify the DNA found in different organisms.

Scene 21:



Chargaff used new techniques for separating nitrogenous bases and found that the same four bases were present in the DNA of every organism he studied. However, earlier beliefs about DNA composition had been wrong. DNA was not just a repeating series of the four bases. Instead the quantity of bases differed in various organisms. There was, however, a definite pattern. The number of Adenines always equaled the number of Thymines and the number of Guanines equaled Cytosines. Chargaff also noted that the quantity of the purines (adenine and guanine) equaled the quantity of pyrimidines (thymine and cytosine) in each organism. These two points were invariable, regardless of the organism studied, and eventually came to be known as **Chargaff's rules**.

Scene 22:

In the early 1950s, an experiment performed by **Alfred Hershey** and **Martha Chase** definitively showed that it was in fact DNA, and not protein, that functioned as the hereditary molecule. The two researchers devised an experiment using a virus called T2. T2 infects bacteria and is known as a **bacteriophage**, or simply phage. Hershey and Chase knew that the T2 phage consists only of DNA and protein, and they knew how it infects cells. T2 phage attaches to bacterial cells and injects its contents while the phage body remains outside the cell. The injected phage contents cause the cell to synthesize new phages until releasing them when the cell eventually bursts. Because the bacterial cell is literally re-programmed to produce phages, the researchers knew that the substance phages inject into bacteria must be hereditary material.

Scene 23:

Hershey and Chase created experimental conditions to test whether phages inject protein or DNA into bacterial cells. The researchers knew that protein contains sulfur, whereas DNA does not. They also knew that DNA contains nearly all the phosphorous in a phage. Therefore, the researchers were able to use radioactive **isotopes** of both phosphorous and sulfur to label these components of the phages. Isotopes, as you may know, are often unstable forms of an element that emit **radioactive** particles of energy that can be detected. By growing phage-infected bacteria in the presence of radioactive phosphorous, the phosphorous isotopes would incorporate into the DNA of any new phage produced. Similarly, by growing phage-infected bacteria with radioactive sulfur present, the new phages would contain radioactive sulfur isotopes in their protein.

Scene 24:

In 1952, Hershey and Chase performed their famous experiment. In separate vessels, they placed phages with radioactive protein and phages with radioactive DNA to see which one would infect the non-radioactive bacteria. Afterward, the bacteria were placed in blenders to remove any phage parts that remained attached to cells after injecting their contents. Next, each mixture was rapidly spun in a **centrifuge**. Since bacteria are heavier than phages, they formed a pellet at the bottom, while the phages remained suspended in solution. Finally, Hershey and Chase measured the radioactivity in the two separate vessels. In the sample containing phages with radioactive protein, most of the radioactivity remained in solution with the phages. In the sample with the radioactive DNA, the radioactivity was in the pellet of bacteria at the bottom, effectively showing that the phages had injected radioactive DNA into the bacteria. This proved to the world that DNA was the hereditary material.

Scenes 25-33
DNA Structure

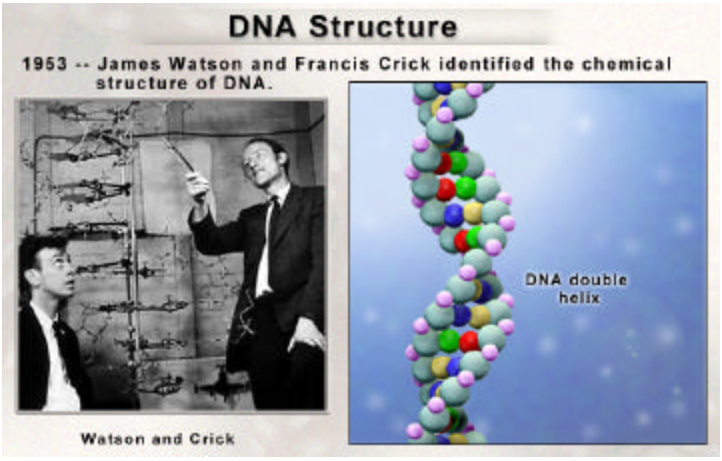
Scene 25:

Once scientists identified DNA as the genetic, or hereditary molecule, the next questions to answer were 1) how does DNA carry information and 2) how can this information be copied every time a cell divides? Knowing the structure of DNA could answer the first question, and perhaps provide information for the second. Fortunately, many clues already existed. P.A. Levene had described the chemical nature of nucleotides, and the bonds that held them together. Chargaff had determined that there is the same amount of adenine as thymine and likewise for cytosine and guanine. The next major clues in determining DNA's structure came from the work of researchers named Maurice Wilkins and Rosalind Franklin who experimented with a technique called **X-ray diffraction**.

Scene 26:

In x-ray diffraction, researchers aim a beam of X-rays at a crystallized form of the substance they wish to analyze. The X-rays interact with atoms in the crystal and come out in a pattern captured on X-ray film. Although DNA does not actually form crystals, the DNA molecule is uniform enough that, when analyzed, the patterns it formed on film showed fine details about its structure. X-ray diffraction revealed DNA to be a large molecule made up of a number of spiraling —or helical— chain-like strands.

Scene 27:

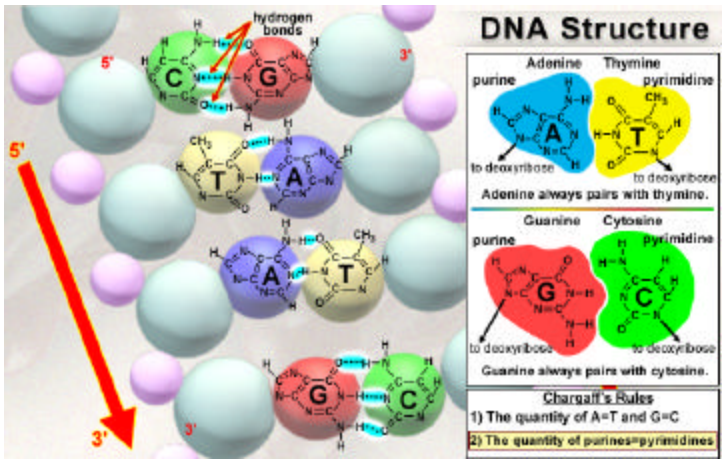


A biologist named **James Watson** and a physicist named **Francis Crick** correctly identified the chemical structure of DNA in 1953. After examining previous DNA research and studying Rosalind Franklin and Maurice Wilkin's X-ray diffraction photos, Watson and Crick came up with a model for the structure that pieced together all parts of the puzzle. The Watson and Crick DNA model had nucleotides arranged in the shape of a **double helix** – a structure resembling a long twisted ladder.

Scene 28:

The two long, chain-like strands that make up the backbones of the double helix are alternating units of sugar and phosphate molecules that form phosphodiester bonds as Levene described in the 1920s. These long strands are commonly referred to as the sugar-phosphate backbones of DNA. The nitrogenous bases comprising each nucleotide exist in the center of the helix, like rungs of a ladder. This orientation protects the bases from water, which could alter their structure, and allows weak bonds, called hydrogen bonds, to form between bases in a manner that holds the two chains of nucleotides together. Hydrogen bonds are quite weak by themselves, but when many hydrogen bonds occur together, they can tightly zip-up a molecule. A similar principle applies to Velcro® in which many tiny hooks and loops firmly fasten one object to another.

Scene 29:



Watson and Crick found the double helix the most stable configuration for DNA. This structure fits the X-ray diffraction data and allowed for hydrogen bonding between bases. In their model, the two strands of DNA run in opposite directions and purines form base pairs with pyrimidines. More specifically, the optimal fit for base pairing occurs when the purine, adenine, binds to the pyrimidine, thymine, and when guanine and cytosine pair together. This orientation of DNA bases fits exactly with Chargaff's rules. Since a purine always binds to a pyrimidine, it explains why there are always equal amounts of purines and pyrimidines in DNA. Additionally, the specific base pairs that form explain why adenine and thymine are equal in amount as well as guanine and cytosine.

Scene 30:

The alignment of the DNA strands in opposite directions is what people refer to when they discuss the **antiparallel** nature of DNA. Earlier, you learned that the phosphodiester bonds holding the sugar phosphate backbone of DNA together occur between the 5' (five prime) end of one sugar molecule and the 3' end of the next. The antiparallel strands of DNA are positioned so that the 5' to 3' orientation of molecules in one strand run in the same direction as the 3' to 5' molecule orientation in the opposite, or **complementary** strand. In other words, one strand of DNA is upside down in relation to the other strand.

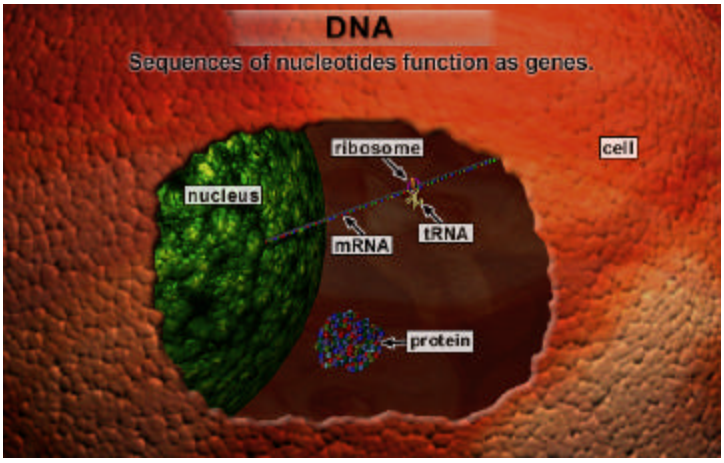
Scene 31:

Watson and Crick realized that their double helix model of DNA — with its antiparallel strands and complementary base pairs -- could easily serve as a template for making new DNA strands. Remember adenine always pairs with thymine and guanine and cytosine always pair together. Simply separating the strands and adding nucleotides to form the appropriate base pairs would generate the opposite or complementary strand of DNA. They also noticed how DNA could function as the genes we inherit from our parents. Since nucleotides were limited only by the partner with which they could form base pairs across the strands, they could exist in almost any ordered sequence along a strand of DNA. Watson and Crick noted that nucleotides arranged in different sequences along each strand of DNA could serve as genes and code for different traits.

Scene 32:

Subsequent studies of DNA structure confirmed the Watson and Crick model to be correct. For their work, they, along with Maurice Wilkins, received the Nobel Prize in 1962. Unfortunately, Rosalind Franklin was not included. She had died previously, and the Nobel Prize is given only to living recipients. The structure of the DNA double helix was visually confirmed in 1969. As you will see in the following scenes, the Watson and Crick DNA model provided the necessary clues for answering how DNA acted as genes and how the genetic information could be copied before a cell divides.

Scene 33:

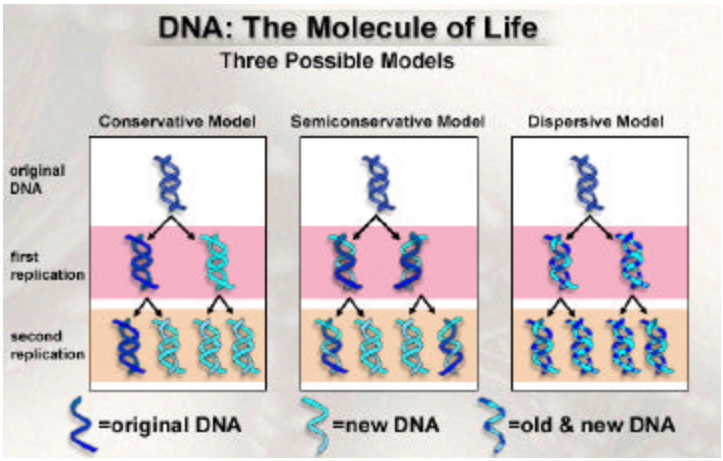


Subsequent studies confirmed that sequences of nucleotides in DNA are, indeed, genetic codes, or genes. When DNA functions as genes, the nucleotides on a single strand of DNA are copied as a single strand of RNA nucleotides. RNA, as you learned earlier, is the other type of nucleic acid found in the cell, and it is primarily found outside the nucleus. Once an RNA copy of DNA is made, it travels out of the nucleus where it interacts with structures responsible for protein synthesis. RNA therefore, acts as a messenger, which transfers DNA's genetic message to other molecules that perform work as coded for by the message. Specific molecules bind to the RNA message, and a chain of amino acids is built in accordance with the sequence of nucleotides. Different sequences of DNA produce RNA coding for different chains of amino acids. The resulting chains of amino acids are eventually folded into the various proteins and enzymes necessary for the survival of the cell or the entire organism. The way in which DNA nucleotides serve as genes that code for proteins, and how proteins influence an organism's traits is a fascinating, but complex topic that can be studied in further detail in a text, or in other Cyber Ed® programs.

Scene 34-43
DNA Replication

Scene 34:

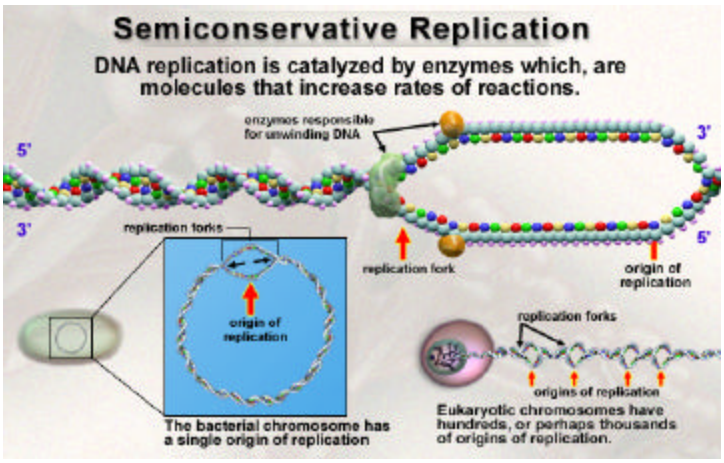
The discovery of DNA structure helped explain not only how DNA functions as genes, but also suggested how DNA could be copied, or replicated, before a cell divides. Watson and Crick surmised DNA could serve as a template for making new DNA strands, but the manner in which DNA replication actually occurred remained a mystery. Researchers conceived three possible models. In what is known as the **conservative model**, the original double stranded DNA molecule remains intact after replication and entirely new copies of both strands are produced. In the **semiconservative model**, the original DNA strands separate and new strands, called **daughter strands**, remain attached to the original, or **parent strands**. In the **dispersive model**, replication occurs in various points along each strand, yielding new strands of DNA that are each a mixture of old and new DNA.



Scene 35:

In the late 1950s, **Matthew Messelson** and **Franklin Stahl** demonstrated DNA undergoes semiconservative replication. They grew bacteria in the presence of either normal weight nitrogen or an isotope of heavier nitrogen, and thus controlled which type of nitrogen was incorporated into new DNA. When this DNA was isolated and spun in a centrifuge, DNA containing heavy nitrogen would form a layer below DNA containing normal nitrogen. To distinguish between conservative, semiconservative, and dispersive replication, the researchers grew cells with DNA containing heavy nitrogen in the presence of normal nitrogen. This was done for one and two rounds of cell division. Then, they harvested the cells and isolated the DNA the cells produced. After the first division, a single layer representing a blend of both normal and heavy DNA was produced. This counted out the conservative model, which would have predicted two layers. After the second division, two layers were produced, one corresponding to all normal weight DNA, and one corresponding to a blend of normal and heavy DNA. As you can see in the diagram, this result confirmed that DNA undergoes the semiconservative model of replication.

Scene 36:



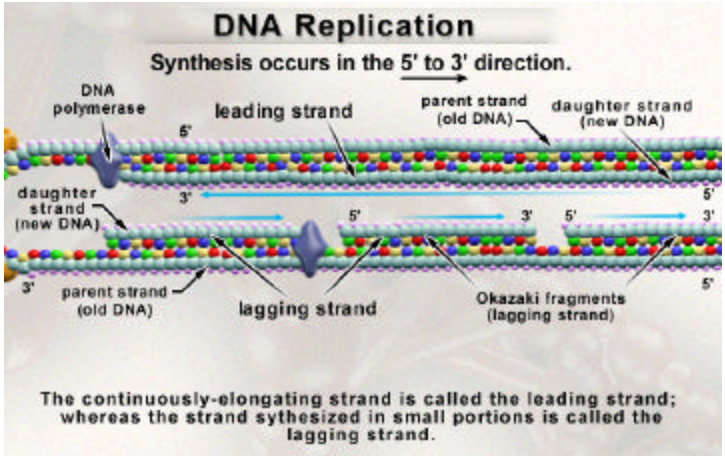
After researchers determined the manner in which DNA replicates, further studies revealed the actual processes involved. DNA replication is catalyzed by **enzymes**, which you may already know are molecules that dramatically speed up chemical reactions. First, enzymes unwind portions of the double helix as the hydrogen bonds holding the strands together separate. This unzipping of the DNA only occurs at very specific points, called **origins of replication**. Just a single origin of replication exists in bacteria, whereas there are hundreds or perhaps thousands of origins of replication in the DNA of eukaryotic organisms. The Y-shape regions resulting at both ends of the separated strands of DNA are called **replication forks**, and the single stranded DNA on both sides of the replication forks serve as templates for new DNA synthesis.

Scene 37:

New DNA is made by linking nucleotides as they form base pairs with single stranded DNA near the replication forks. Nucleotides actually come from the food we eat, and special enzymes process them for use in DNA synthesis. An enzyme called **DNA polymerase** attaches incoming nucleotides to the growing strand by forming the same phosphodiester bonds between the sugar and phosphate molecules that you learned about earlier. The energy required to create these bonds comes from the incoming nucleotides, which are actually in the form of **nucleoside triphosphates**, meaning they have three phosphate groups. Much like reactions involving ATP, which you've probably learned about as a molecule that drives many cellular reactions, the energy for making the phosphodiester bonds is liberated through the removal of phosphate groups. DNA polymerase then binds each resulting nucleotide to the adjacent nucleotide in the elongating DNA daughter strand.

Scene 38:

DNA polymerase rapidly links the sugar and phosphate molecules of nucleotides together, but it can only bond incoming nucleotides to the 3' end of a growing strand – that is, it can only synthesize DNA by moving in the 5' to 3' direction. Earlier you learned DNA is antiparallel, meaning that when one strand is oriented in the 3' to 5' direction, the other is oriented 5' to 3'. Therefore, at each replication fork one parent strand is oriented so that one daughter strand elongates continuously in the 5' to 3' direction. Along the other parent strand, DNA polymerase works away from the replication fork, creating small pieces and then waiting for new sections of DNA to unwind and open before continuing in the 5' to 3' direction. The continuously elongating strand is called the **leading strand,** whereas the strand synthesized in small portions is called the **lagging strand**. The small fragments of DNA in the lagging strand are named **Okazaki fragments**, in honor of the researcher, Okazaki, who discovered them.



Scene 39:

Though DNA polymerase links nucleotides together, it cannot actually begin DNA synthesis because it only adds nucleotides to a pre-existing strand. For DNA synthesis to occur, a short piece of RNA called a **primer** is made by yet another enzyme and pairs with complementary bases on the parent strand. DNA polymerase then links a nucleotide to the RNA primer before it continues linking DNA nucleotides together in the 5' to 3' direction. As you can see, the leading strand requires only one primer, whereas each Okazaki fragment in the lagging strand needs its own primer. Eventually, the primer is clipped out and replaced with DNA. To complete DNA synthesis, and thus replication of the DNA molecule, another enzyme called DNA **ligase** attaches the Okazaki fragments together to form a continuous strand of DNA.

Scene 40:

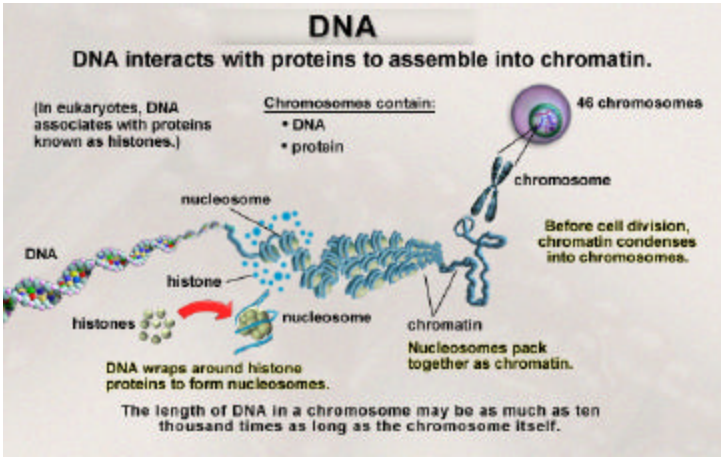
DNA replication is surprisingly rapid and efficient. For example, replication of the bacterial chromosome, which consists of approximately 5 million base pairs, can occur in as little as twenty minutes. The 46 chromosomes of human cells consist of around 3 billion base pairs. The entire DNA in these cells can be replicated in a matter of hours. However, during replication, sometimes a few mistakes are made. Incoming nucleotides that incorrectly pair with the parent strand nucleotides occur at a rate of around one in ten thousand base pairs. However, the rate of incorrectly paired nucleotides in completed DNA is around one in one billion. The reason for this difference is specialized DNA repair enzymes that correct defective DNA.

Scene 41:

There are several methods for repairing damaged DNA, and they vary in different types of organisms. However, a general method involves enzymes that cut out a damaged or improperly paired portion of DNA. Next, new nucleotides come in and form base pairs with the complementary strand. Finally, DNA polymerase and ligase bind the new nucleotides to the strand to form a properly base paired DNA molecule. DNA repair systems also aid in repairing DNA damage done by factors such as chemicals and ultraviolet light, which can cause medical problems like cancer in humans.

Scene 42:

At this point, you may be wondering the fate of newly synthesized DNA. Earlier, you learned that chromosomes contain both protein and DNA. Once DNA replicates, negative charges associated with the phosphate groups interact with groups of positively charged protein molecules called **histones** (in eukaryotes), and other proteins. DNA wraps around the histones and assembles into units called **nucleosomes**, which then tightly pack together as chromatin. Long strands of chromatin can condense further to become the chromosomes. The length of DNA in a chromosome may be as much as ten thousand times as long as the chromosome itself. This dramatic compacting accounts for the chromosomes' ability to hold enough DNA, and therefore genes, to direct the assembly of proteins and other molecules used to build cells and maintain living organisms. In fact, the DNA contained in the forty-six human chromosomes is believed to account for tens of thousands of genes.



Scene 43:

Major steps in the sciences of biology, medicine, chemistry, and physics contributed to the discovery of DNA as the hereditary material. You now know why the tiger cub in the first scene resembles its parents. It inherited chromosomes carrying DNA with genes for tiger traits. You've learned the actual chemical structure of the DNA double helix, and you've been introduced to how sequences of nucleotides comprising DNA function as genes. You've also learned the process of DNA replication and how errors occurring during DNA replication are repaired. During the time it took to work through this program, you've learned valuable information about the life sustaining substance called DNA, that took scientists hundreds of years to understand.

Quiz One
Introduction and the Search for Heredity

1. The term bloodline accurately describes heredity because DNA is carried to offspring through the mother's blood.
   A. True
   B. False

2. Traits that are typically expressed even if an offspring inherits just one copy of a gene for the trait are called _____traits.
   A. dominant
   B. recessive
   C. expressive
   D. none of the above

3. There is/are _____ gene(s) on a single chromosome
   A. one
   B. zero – unless the chromosome is very long
   C. many
   D. twenty-three

4. Traits that typically will only be expressed in offspring if they inherit two copies of the genes for the trait are called _____traits.
   A. dominant
   B. recessive
   C. expressive
   D. none of the above

5. Thomas Hunt Morgan determined that genes for various traits are arranged in a specific order along chromosomes.
   A. True
   B. False

6. Chromosomes contain both _____ and _____.
   A. nucleotides, organelles
   B. phage, protein
   C. enzymes, DNA
   D. protein, DNA

7. Although DNA structure was determined in the 1950's, the role of DNA in carrying hereditary units has been well known for thousands of years.
   A. True
   B. False

8. DNA is found primarily in the cell _____; whereas RNA is found primarily in the cell _____.

A. membrane, wall
B. cytoplasm, nucleus
C. organelles, cytosol
D. nucleus, cytoplasm

9. Chromatin condenses into dense, darkly staining structures called _____ prior to cell division.

A. nuclei
B. nucleosomes
C. chromosomes
D. all of the above

10. Genes are _____.

A. highly folded protein units
B. sequences of DNA nucleotides
C. sequences of RNA nucleotides
D. hundreds of amino acids

Quiz Two

Determining DNA Composition and Its Role in Heredity

1. P.A. Levene determined that DNA is composed of _____.
   A. lipids, carbohydrates, and fatty acids
   B. phosphorus and sulfur
   C. the sugar deoxyribose, phosphate groups, and nitrogenous bases
   D. the sugar ribose, phosphate groups, and nitrogenous bases

2. When Fredrick Griffith injected mice with a mixture of both heat-killed smooth strain bacteria (which cause disease when living) and live rough strain bacteria (which do not cause disease), an unexpected result occurred. This result was _____.
   A. the mice all lived
   B. the mice died but then came back to life
   C. the mice died because rough strain bacteria had been transformed to the smooth strain
   D. none of the above

3. Avery, MacLeod, and McCarty found _____ transformed live rough strain bacteria to smooth strain cells, and therefore, was genetic material.
   A. DNA
   B. lipids
   C. carbohydrates
   D. RNA

4. Hershey and Chase used radioactive isotopes to label phage protein and phage DNA before allowing the phages to infect bacteria. When they found that radioactive phosphorous had been injected into bacteria, they knew DNA was genetic material. Why?
   A. DNA contains nearly all the phosphorous in a phage.
   B. If protein had been injected, they would have found radioactive sulfur.
   C. They guessed.
   D. Both A and B.

5. Adenine and guanine are _____; whereas thymine and cytosine are _____.
   A. pyrimidines, purines
   B. pachytene, polytene
   C. purines, pyrimidines
   D. bases, phosphate groups

6. What are the four types of nitrogenous bases found in DNA?
   A. Adenine, guanine, cytosine, and uracil
   B. Phosphorus, nitrogen, deoxyribose, and phosphate groups
   C. Lipid, sulfur, carbohydrate, and phosphorus

D. Adenine, guanine, cytosine, and thymine

7. In DNA, adenine always pairs with _____, while guanine always pairs with _____.
   A. guanine, thymine
   B. thymine, cytosine
   C. cytosine, adenine
   D. guanine, adenine

8. A DNA nucleotide consists of:
   A. a protein coat, lipids, carbohydrates, and DNA.
   B. lipids, carbohydrates, and one of four nitrogenous bases.
   C. the sugar deoxyribose, a phosphate group, and one of four nitrogenous bases.
   D. the sugar deoxyribose, protein, nitrogenous bases and sulfur groups.

9. Erwin Chargaff discovered there are not equal amounts of all four nitrogenous bases in an organism. However, the amount of adenine always equals the amount of thymine, and likewise, the amount of guanine equals cytosine in any organism. This became known as part of _____.
   A. the chromosomal theory of inheritance
   B. Koch' s postulates
   C. natural selection
   D. Chargaff's rules

10. The sugar molecules found in DNA nucleotides are _____.
   A. ribose
   B. sucrose
   C. deoxyribose
   D. dextrose

Quiz Three
DNA Structure

1. The type of bond that links two nucleotides together in a strand of DNA is known as a/an _____.
   A. hydrogen bond
   B. phosphodiester bond
   C. nucleotic bond
   D. none of the above

2. DNA has two sugar-phosphate backbones and variable sequences of nitrogenous bases that form complementary pairs between the sugar-phosphate backbones.
   A. True
   B. False

3. Watson and Crick are famous for discovering _____.
   A. the structure of DNA
   B. the chemical components of DNA
   C. the life cycle of a phage
   D. radioactive isotopes

4. Which phrase best describes the structure of DNA?
   A. A twisted single strand
   B. A fireman's ladder
   C. A double helix
   D. A triple helix

5. The technique that uses x-rays to aid in identifying chemical structures is called _____.
   A. X-ray centrifugation
   B. X-ray ingestion
   C. X-ray diffraction
   D. X-ray infraction

6. The multiple, relatively weak bonds between complementary nitrogenous bases that hold double stranded DNA together are known as _____.
   A. nitrogen bonds
   B. phosphodiester bonds
   C. retainer bonds
   D. hydrogen bonds

7. The sugar-phosphate backbones of the DNA double helix are oriented in opposite directions. This is commonly referred to as the _____ nature of DNA.

A. antigenic
B. antiparallel
C. anticlimactic
D. antiquated

8. How many different nucleotides are found in the DNA double helix?

A. 2
B. 4
C. 6
D. 20

9. Nitrogenous bases, such as adenine and thymine, that pair together by forming hydrogen bonds between two strands of DNA are said to be _____.

A. sedimentary
B. elementary
C. rudimentary
D. complementary

10. When DNA functions as genes, first a single strand of ____is made, and then a chain of _____ is built, which subsequently folds to become a(n) _____.

A. RNA, amino acids, protein
B. amino acids, RNA, protein
C. protein, RNA, amino acid
D. RNA, protein, amino acid

Quiz Four
DNA Replication

1. During DNA replication _____.
   A. the DNA strands separate and become templates for new DNA synthesis
   B. the bases become unattached from the parent strand and reassemble
   C. the DNA molecule disintegrates in the cell
   D. the DNA strands "zip" together and prevent complementary bases from pairing

2. After semi-conservative replication is complete, how many daughter strands are produced and how many parent strands remain?
   A. Three daughter strands are produced from the remaining single parent strand.
   B. Two daughter strands are produced from the remaining two parent strands.
   C. Zero parent strands remain and four daughter strands are produced.
   D. None of the above are produced.

3. There is just a single origin of replication in bacterial DNA; whereas there are hundreds or perhaps thousands of origins of replication in the DNA of eukaryotic organisms.
   A. True
   B. False

4. When the wrong nucleotides are added to a strand of DNA during DNA replication, they can never be repaired.
   A. True
   B. False

5. Once eukaryotic DNA has replicated, it condenses when negatively charged phosphate groups interact with positively charged protein molecules known as _____.
   A. histones
   B. hemoglobin
   C. antibodies
   D. keratin

6. DNA wraps around histones and assembles into units called _____, which are then tightly packed together as chromatin.
   A. packosomes
   B. condensosomes
   C. nucleosomes
   D. none of the above

7. The enzyme that attaches nucleotides together by forming phosphodiester bonds between sugar and phosphate molecules during DNA replication is known as _____.

A. helicase
B. reverse transcriptase
C. DNA replicase
D. DNA polymerase

8. The continually elongating strand of new DNA at one side of a replication fork during DNA replication is known as the _____ strand.

A. lagging
B. quick
C. leading
D. sagging

9. During DNA replication, the short sections of new DNA, known as Okazaki fragments, which are eventually linked together by ligase are known as the _____ strand.

A. lagging
B. quick
C. leading
D. sagging

10. For DNA polymerase to link nucleotides together as new strands of DNA, the first nucleotide must be attached to a _____ because DNA polymerase can only add nucleotides to a pre-existing strand.

A. protein
B. enzyme
C. RNA primer
D. chromosome

Key to Quizzes

Quiz 1 Key	Quiz 2 Key	Quiz 3 Key	Quiz 4 Key
1.B	1.C	1.B	1.A
2.A	2.C	2.A	2.B
3.C	3.A	3.A	3.A
4.B	4.D	4.C	4.B
5.A	5.C	5.C	5.A
6.D	6.D	6.D	6.C
7.B	7.B	7.B	7.D
8.D	8.C	8.B	8.C
9.C	9.D	9.D	9.A
10.B	10.C	10.A	10.C

Comprehensive Multiple Choice Exam

1. Frederick Griffith discovered that hereditary material could be transferred from one bacterium to another. He called this phenomenon transformation.
   A. True
   B. False

2. When Fredrick Griffith injected mice with a mixture of both heat-killed smooth strain bacteria (which cause disease when living) and live rough strain bacteria (which do not cause disease), an unexpected result occurred. This result was _____.
   A. the mice all lived
   B. the mice died but then came back to life
   C. the mice died because rough strain bacteria had been transformed to the smooth strain
   D. none of the above

3. Avery, MacLeod, and McCarty found _____ transformed live rough strain bacteria to smooth strain cells, and therefore, was genetic material.
   A. DNA
   B. lipids
   C. carbohydrates
   D. RNA

4. The bacteriophage used by Hershey and Chase consisted of two types of molecules: _____ and _____.
   A. lipids, carbohydrates
   B. lipids, protein
   C. DNA, protein
   D. DNA, lipids

5. When a phage attaches to a bacterium, the phage injects _____ and the _____ stay(s) attached to the cell membrane.
   A. protein, phage body
   B. DNA, phage body
   C. lipid, DNA bases
   D. DNA, lipid molecules

6. Hershey and Chase used radioactive isotopes to label phage protein and phage DNA before allowing the phages to infect bacteria. When they found that radioactive phosphorous had been injected into bacteria, they knew DNA was genetic material. Why?
   A. DNA contains nearly all the phosphorous in a phage.
   B. If protein had been injected, they would have found radioactive sulfur.
   C. They guessed.
   D. Both A and B.

7. Adenine and guanine are _____; whereas thymine and cytosine are _____.
   A. pyrimidines, purines
   B. pachytene, polytene
   C. purines, pyrimidines
   D. bases, phosphate groups

8. The two pyrimidines in DNA are _____. The two purines are _____.
   A. cytosine & thymine, guanine & adenine
   B. thymine & guanine, adenine & cytosine
   C. guanine &adenine, thymine & cytosine
   D. guanine & cytosine, adenine & thymine

9. P.A. Levene determined that DNA is composed of _____.
   A. lipids, carbohydrates, and fatty acids
   B. phosphorus and sulfur
   C. the sugar deoxyribose, phosphate groups, and nitrogenous bases
   D. the sugar ribose, phosphate groups, and nitrogenous bases

10. What are the four types of nitrogenous bases found in DNA?
   A. Adenine, guanine, cytosine, and uracil
   B. Phosphorus, nitrogen, deoxyribose, and phosphate groups
   C. Lipid, sulfur, carbohydrate, and phosphorus
   D. Adenine, guanine, cytosine, and thymine

11. In DNA, adenine always pairs with _____, while guanine always pairs with _____.
   A. guanine, thymine
   B. thymine, cytosine
   C. cytosine, adenine
   D. guanine, adenine

12. A DNA nucleotide consists of:
   A. a protein coat, lipids, carbohydrates, and DNA.
   B. lipids, carbohydrates, and one of four nitrogenous bases.
   C. the sugar deoxyribose, a phosphate group, and one of four nitrogenous bases.
   D. the sugar deoxyribose, protein, nitrogenous bases and sulfur groups.

13. How many different nucleotides are found in the DNA double helix?
    A. 2
    B. 4
    C. 6
    D. 20

14. Watson and Crick are famous for discovering _____.
    A. the structure of DNA
    B. the chemical components of DNA
    C. the life cycle of a phage
    D. radioactive isotopes

15. Which phrase best describes the structure of DNA?
    A. A twisted single strand
    B. A fireman's ladder
    C. A double helix
    D. A triple helix

16. DNA has two sugar-phosphate backbones and variable sequences of nitrogenous bases that form complementary pairs between the sugar-phosphate backbones.
    A. True
    B. False

17. During DNA replication_____.
    A. the DNA strands separate and become templates for new DNA synthesis
    B. the bases become unattached from the parent strand and reassemble
    C. the DNA molecule disintegrates in the cell
    D. the DNA strands "zip" together and prevent complementary bases from pairing

18. After semi-conservative replication is complete, how many daughter strands are produced and how many parent strands remain?
    A. Three daughter strands are produced from the remaining single parent strand.
    B. Two daughter strands are produced from the remaining two parent strands.
    C. Zero parent strands remain and four daughter strands are produced.
    D. None of the above are produced.

19. What is the name of the DNA replication process that produces two identical DNA molecules, each consisting of one parent strand and one daughter strand?

A. Conservative DNA replication
B. Parent-daughter DNA replication
C. Dispersive DNA replication
D. Semiconservative DNA replication

20. There is just a single origin of replication in bacterial DNA; whereas there are hundreds or perhaps thousands of origins of replication in the DNA of eukaryotic organisms.

A. True
B. False

21. The term bloodline accurately describes heredity because DNA is carried to offspring through the mother's blood.

A. True
B. False

22. Traits that are typically expressed even if an offspring inherits just one copy of a gene for the trait are called _____traits.

A. dominant
B. recessive
C. expressive
D. none of the above

23. Traits that typically will only be expressed in offspring if they inherit two copies of the genes for the trait are called _____traits.

A. dominant
B. recessive
C. expressive
D. none of the above

24. DNA is found primarily in the cell _____; whereas RNA is found primarily in the cell _____.

A. membrane, wall
B. cytoplasm, nucleus
C. organelles, cytosol
D. nucleus, cytoplasm

25. Chromatin condenses into dense, darkly staining structures called _____ prior to cell division.

A. nuclei
B. nucleosomes
C. chromosomes
D. all of the above

26. There is/are _____ gene(s) on a single chromosome.
    A. one
    B. zero – unless the chromosome is very long
    C. many
    D. twenty three

27. Thomas Hunt Morgan determined that genes for various traits are arranged in a specific order along chromosomes.
    A. True
    B. False

28. Chromosomes contain both _____ and _____.
    A. nucleotides, organelles
    B. phage, protein
    C. enzymes, DNA
    D. protein, DNA

29. The sugar molecules found in DNA nucleotides are _____.
    A. ribose
    B. sucrose
    C. deoxyribose
    D. dextrose

30. A phosphorous atom surrounded by four oxygen atoms is commonly called a _____.
    A. nucleotide
    B. nitrogenous base
    C. sugar-phosphate backbone
    D. phosphate group

31. The type of bond that links two nucleotides together in a strand of DNA is known as a/an _____.
    A. hydrogen bond
    B. phosphodiester bond
    C. nucleotic bond
    D. none of the above

32. Numbering the carbon atoms in the DNA sugar, deoxyribose, helps to _____.
    A. describe the molecule and discuss where specific bonds form
    B. see parts of the molecule under a microscope
    C. direct DNA polymerase during DNA replication
    D. all of the above

33. Erwin Chargaff discovered there are not equal amounts of all four nitrogenous bases in an organism. However, the amount of adenine always equals the amount of thymine, and likewise, the amount of guanine equals cytosine in any organism. This became known as part of _____.

A. the chromosomal theory of inheritance
B. Koch' s postulates
C. natural selection
D. Chargaff's rules

34. A virus that infects bacteria is known as a _____.

A. living organism
B. bacteriophage
C. phagobacter
D. prokaryote

35. The technique that uses x-rays to aid in identifying chemical structures is called _____.

A. X-ray centrifugation
B. X-ray ingestion
C. X-ray diffraction
D. X-ray infraction

36. The multiple, relatively weak bonds between complementary nitrogenous bases that hold double-stranded DNA together are known as _____.

A. nitrogen bonds
B. phosphodiester bonds
C. retainer bonds
D. hydrogen bonds

37. The sugar-phosphate backbones of the DNA double helix are oriented in opposite directions. This is commonly referred to as the _____ nature of DNA.

A. antigenic
B. antiparallel
C. anticlimactic
D. antiquated

38. Nitrogenous bases, such as adenine and thymine, that pair together by forming hydrogen bonds between two strands of DNA are said to be _____.

A. sedimentary
B. elementary
C. rudimentary
D. complementary

39. When DNA functions as genes, first a single strand of ____is made, and then a chain of _____ is built, which subsequently folds to become a(n) _____.
A. RNA, amino acids, protein
B. amino acids, RNA, protein
C. protein, RNA, amino acid
D. RNA, protein, amino acid

40. The enzyme that attaches nucleotides together by forming phosphodiester bonds between sugar and phosphate molecules during DNA replication is known as _____.
A. helicase
B. reverse transcriptase
C. DNA replicase
D. DNA polymerase

41. The continually elongating strand of new DNA at one side of a replication fork during DNA replication is known as the _____ strand.
A. lagging
B. quick
C. leading
D. sagging

42. During DNA replication, the short sections of new DNA, known as Okazaki fragments, which are eventually linked together by ligase are known as the _____ strand.
A. lagging
B. quick
C. leading
D. sagging

43. For DNA polymerase to link nucleotides together as new strands of DNA, the first nucleotide must be attached to a _____ because DNA polymerase can only add nucleotides to a pre-existing strand.
A. protein
B. enzyme
C. RNA primer
D. chromosome

44. The DNA replication enzyme that attaches Okazaki fragments together as a continuous strand of DNA is called _____.
A. combinase
B. ligase
C. gluease
D. bindase

45. When the wrong nucleotides are added to a strand of DNA during DNA replication, they can never be repaired.
    A. True
    B. False

46. Once DNA has replicated, it condenses when negatively charged phosphate groups interact with positively charged protein molecules known as _____.
    A. histones
    B. hemoglobin
    C. antibodies
    D. keratin

47. In eukaryotes, DNA wraps around histones and assembles into units called _____, which are then tightly packed together as chromatin.
    A. packosomes
    B. condensosomes
    C. nucleosomes
    D. none of the above

48. The length of DNA in a chromosome may be as much as 10,000 times as long as the chromosome itself.
    A. True
    B. False

49. Although DNA structure was determined in the 1950's, the role of DNA in carrying hereditary units has been well known for thousands of years.
    A. True
    B. False

50. Genes are _____.
    A. highly folded protein units
    B. sequences of DNA nucleotides
    C. sequences of RNA nucleotides
    D. a single amino acids

Multiple Choice Exam Key

1. A	11. B	21. B	31. B	41. C
2. C	12. C	22. A	32. A	42. A
3. A	13. B	23. B	33. D	43. C
4. C	14. A	24. D	34. B	44. B
5. B	15. C	25. C	35. C	45. B
6. D	16. A	26. C	36. D	46. A
7. C	17. A	27. A	37. B	47. C
8. A	18. B	28. D	38. D	48. A
9. C	19. D	29. C	39. A	49. B
10.D	20. A	30. D	40. D	50. B

DNA Upgrade Glossary

acid: a substance that releases hydrogen (H^+) ions in water. Acidic solutions have a pH below 7.0.

adenine: one of four nitrogenous bases found in DNA. Adenine forms base pairs with thymine.

alkali: also known as base, a substance that releases hydroxide (OH^-) ions in water. Basic solutions have a pH above 7.0.

antiparallel: when used in reference to DNA, antiparallel refers to the orientation of the sugar phosphate backbones of double-stranded DNA running in opposite directions.

bacteria: single-celled prokaryotic organisms.

bacteriophage: a virus that infects bacteria.

base: a substance that releases hydroxide ions (OH^-) in water. Basic solutions have a pH above 7.0. See nitrogenous base for a definition of DNA base molecules.

centrifuge: a device that spins rapidly and uses this spinning, or centrifugal, force to separate particles of different densities.

Chargaff's rules: statements describing certain invariable properties of DNA, which can be stated as follows: the number of adenine molecules in an organism's DNA always equals the number of thymines, and the number of guanines equals the number of cytosines. Also, the number of the purines (adenine and guanine) equals the number of pyrimidines (thymine and cytosine) in each organism.

chromatin: DNA associated with histones and other proteins that assumes the shape of long thread-like fibers.

chromosome: units of highly condensed and compacted chromatin, which are visible in the cell prior to cell division. Chromosomes consist of DNA, and therefore, the genes that pass from parent to offspring.

complementary pairs (base pairs): nitrogenous bases that follow Chargaff's rules. Adenine and thymine are complementary pairs because adenine always pairs with thymine, and likewise, guanine and cytosine are complementary pairs.

complementary strand: a single DNA strand containing nitrogenous bases in a sequence that precisely forms base pairs with another DNA strand.

cytoplasm: the cell contents between the plasma membrane and the nuclear envelope.

cytosine: one of four nitrogenous bases found in DNA. Cytosine forms base pairs with guanine.

daughter strand (DNA): a new strand of DNA that is complementary to the original, parent strand from which it is synthesized.

deoxyribose: the five-carbon sugar molecule found in each DNA nucleotide. Deoxyribonucleic acid derives part of its name from this molecule.

deoxyribonucleic acid (DNA): the double helix of nucleotides that functions as hereditary material as it is passed through generations in all living organisms.

DNA double helix: the long, twisted-ladder shaped structure comprised of two strands of nucleotides running in opposite directions. The DNA strands of the double helix are held together by hydrogen bonds between complementary bases.

DNA polymerase: an enzyme that catalyzes DNA replication by linking incoming nucleotides together as an elongating DNA daughter strand.

DNA replication: the process of creating new copies of DNA. DNA undergoes semiconservative replication.

egg: the female's gamete (sex cell) which may combine with the male's sperm to produce a new organism.

enzyme: a molecule that greatly increases the rate of chemical reactions or allows a reaction to occur under less than optimal conditions.

gene: a discrete unit of DNA nucleotides that codes for a particular trait or characteristic.

guanine: one of four nitrogenous bases found in DNA. Guanine forms base pairs with cytosine.

heredity: the passing of genes, or traits, from parent to offspring.

histone: positively charged protein molecules that interact with negatively charged phosphate groups in DNA. DNA wraps around groups of histones and other proteins to assemble into nucleosomes, which assemble into chromatin.

isotope: an atom of an element that has a different number of neutrons in its nucleus than normal. Isotopes are often unstable and emit small particles of radioactive energy that can be measured.

lagging strand (DNA): short sections of DNA (Okazaki fragments) synthesized in the 5' to 3' direction along the DNA parent strand that opens up in the 3' to 5' direction. Synthesis of lagging strand DNA occurs as DNA polymerase moves away from the replication fork.

leading strand (DNA): the continually elongating strand of DNA synthesized in the 5' to 3' direction along the parent strand that opens up in the 5' to 3' direction. Synthesis of leading strand DNA occurs as DNA polymerase moves toward the replication fork.

ligase: an enzyme that attaches the Okazaki fragments of the lagging strand together to form a continuous strand of DNA during DNA replication.

meiosis: a process in which a cell's genetic material is duplicated and divides twice to yield four new cells with exactly half as much genetic material. Meiosis typically leads to formation of sex cells.

mitosis: a process in which a cell's genetic material is duplicated before it divides equally into two cells.

nitrogenous base: one of the four nitrogen-rich purine or pyrimidine base molecules responsible for forming the hydrogen bonds that hold double stranded DNA together. There are two pyrimidines: thymine and cytosine, and two purines: adenine and guanine in DNA.

nuclein: a term coined by Frederick Meishcer for the grayish substance he observed after treating the cell nucleus with acid and then alkali. We now know nuclein to be chromatin.

nucleoside triphosphate: a nitrogenous base molecule attached to a sugar molecule and three phosphate groups. Two of the three phosphate groups are removed from nucleoside triphosphates as the resulting nucleotides are incorporated into growing DNA strands.

nucleosome: units of DNA associated with histones and other proteins that pack tightly together as chromatin.

nucleotide: a building block of DNA. Each of the four DNA nucleotides contains a single deoxyribose sugar, a phosphate group, and one of four nitrogenous base molecules.

nucleus: the double membrane bound region within eukaryotic cells that houses genetic material.

Okazaki fragments: small fragments of DNA comprising the lagging strand during DNA synthesis. Okazaki fragments are named after the researcher who first described them.

origins of replication: the specific regions where double-stranded DNA opens up prior to DNA replication.

parent strand (DNA): each single strand of the double-stranded DNA double helix, which separate during DNA replication. DNA undergoes semiconservative replication in which new daughter strands are made that form base pairs with the parent strands.

pedigree: a family tree illustrating the inheritance of genes, or various traits or characteristics coded for by genes.

phage: see bacteriophage.

phosphate group: a phosphorous atom surrounded by four oxygen atoms.

phosphodiester bond: the type of bond that links the sugar-phosphate backbone of DNA together.

pneumococcus: the abbreviated name for *Streptococcus pneumoniae,* the bacterium capable of causing the disease pneumonia.

primer: a short piece of RNA that binds to single-stranded DNA near a replication fork. DNA nucleotides bind to the primer at the beginning of DNA synthesis.

prokaryote: a unicellular organism in which DNA is not enclosed in a nucleus.

protein: a molecule composed of many amino acid subunits folded into a specific form. Proteins act as enzymes, cellular transporters, and structural materials, among other things.

purine: one of the two types of nitrogenous bases found in DNA nucleotides. Purines are five-membered rings made of carbon, nitrogen, hydrogen and oxygen attached to a six-membered pyrimidine type of ring. There are two purines, known as adenine and guanine, in DNA.

pyrimidine: one of the two types of nitrogenous bases found in DNA nucleotides. Pyrimidines are six-membered rings made of carbon, nitrogen, hydrogen and oxygen. There are two pyrimidines, known as thymine and cytosine, in DNA.

radioactive: capable of emitting, or radiating, energy in the form of particles or rays from a decaying atom.

replication forks: Y-shaped regions at both ends of the separated DNA parent strands that serve as templates for new DNA synthesis.

ribonucleic acid (RNA): the type of nucleic acid found mainly in the cytoplasm, which plays a large role in the production of proteins. RNA differs from DNA in that it is always single stranded; the sugar molecules are ribose instead of the DNA sugar, deoxyribose; and the DNA base thymine is replaced with uracil in RNA.

ribose: the five-carbon sugar molecule found in each RNA nucleotide. Ribonucleic acid derives part of its name from this molecule.

rough strain pneumococcus: a form of the pneumococcus bacterium that does not cause pneumonia.

semiconservative replication: the manner in which DNA replication occurs. When double-stranded DNA separates to yield two single parent strands, daughter strands are made that form complementary base pairs to the original parent strands.

sex chromosome: a chromosome that determines the gender (sex) of an organism.

smooth strain pneumococcus: a form of the pneumococcus bacterium that causes pneumonia.

sugar: an often sweet tasting carbohydrate molecule. In DNA, each nucleotide contains the sugar deoxyribose.

thymine: one of four nitrogenous bases found in DNA. Thymine forms base pairs with adenine.

trait: a distinguishable characteristic of an organism.

transformation: the transfer of DNA into a cell.

vaccine: a harmless molecule or variant of a disease-causing organism which stimulates the immune system to mount an immune response against the organism if it is later encountered.

X-chromosome: one of two sex chromosomes that determine the gender of an organism. Females have two X-chromosomes; whereas males have one X and one Y-chromosome.

X-ray diffraction: a process in which X-rays are aimed at a crystalline form of a substance and the X-rays interact with the substance and re-emerge in a pattern that can be captured on X-ray film.

Y-chromosome: one of two sex chromosomes that determine the gender of an organism. Females have two X-chromosomes; whereas males have one X and one Y-chromosome.