THEME V

Genetics and Molecular Biology

19

DNA Structure and Function

GENETIC MATERIAL: A JOB DESCRIPTION

During the 1940s and 1950s, several scientists conducted research to determine if it was the protein or the DNA within a cell's chromosomes that contained the genetic material. As a result of careful experiments and chemical analyses, they discovered that **DNA** (**d**eoxyribo**n**ucleic **a**cid) contains the information on which all life depends; that is, DNA *is* the genetic material. A substance that serves as the genetic material has the most significant job in the world: to carry on life itself. In order to carry out this job, the genetic material must do the following:

- It must be able to store information that can be passed on from one generation of cells to the next. It must be able to store enough information to make an organism like a tree or like you.
- It must be able to make a copy of itself in order to pass its information on again and again.
- It must be strong and stable so that it does not easily fall apart and cause perhaps harmful changes to its store of information.
- It must be able to mutate, or change, slightly from time to time. These changes allow a species to produce the variations on which natural selection acts, which can lead to the evolution of new species.

We can now look at how DNA is built and how it functions in order to do these jobs.

THE WORLD LEARNS OF THE DOUBLE HELIX

DNA is made up of smaller **subunits**. These subunits, or **nucleotides**, include four types of bases, which occur in two pairs. The amounts of adenine (A) and thymine (T) are always the same (A pairs with T). The amounts of guanine (G) and cytosine (C) are always the same (G pairs with C). In 1953, scientists James Watson and Francis Crick described the structure of DNA for the first time, as a double helix. (See Figure 19-1.)

To understand the double helix structure of DNA, picture a ladder that has been twisted.

Figure 19-1 Scientists James Watson (left) and Francis Crick (right) shown in 1953 with their model of part of a DNA molecule.

The two sides of the ladder are parallel to each other, and the steps of the ladder link the two sides together. The sides of the ladder are the backbone of the DNA molecule (composed of sugar and phosphate molecules). Stretching between the two sides are the pairs of bases. The Watson-Crick model showed that the only possible way all the parts could fit was for each large adenine base to be matched opposite a smaller thymine base. Similarly, the large guanine had to be opposite a smaller cytosine. (See Figure 19-2.)

So, a molecule of DNA consists of two strands, opposite each other, connected by matching base pairs. If we look at one strand, we can describe it in terms of the order, or sequence, of its subunits. Because the subunits are in a long line, the order of the subunits is called a *linear sequence*. This linear sequence of nucleotides builds the DNA molecule, which may be very long. (Recall that long molecules such as DNA, which can contain thousands of nucleotides in a sequence, are called *polymers*.)

Imagine walking along a single strand of DNA. The bases in the subunits may occur in any order. The linear sequence on a short molecule of DNA might be A-T-T-G-A-C-C-G. Now imagine walking along the opposite strand, starting at the same place. Opposite the A in the first strand is a T. Because we know the sequence of bases in the first strand we automatically know the sequence of bases in the other strand. In this example, beginning with the T, the sequence must be T-A-A-C-T-G-G-C. This is the key to how the DNA molecule copies itself. The process by which DNA copies itself depends on the matching base pairs in the subunits of each strand. What is so important about the order of the subunits in a strand of DNA? The sequence of bases in the subunits *is* the genetic information that the strand of DNA contains. (See Figure 19-3.)

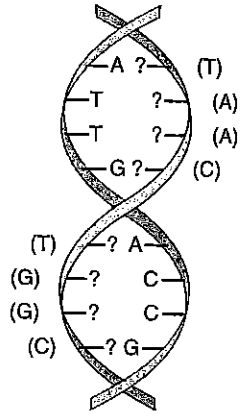


Figure 19-3 From the sequence of bases on one strand of DNA, we can determine the sequence on the opposite strand: A pairs with T, and C pairs with G.

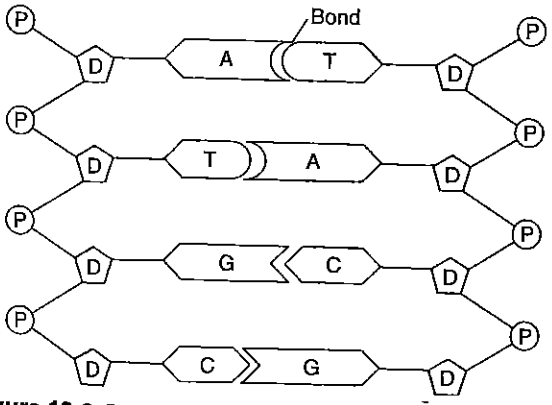


Figure 19-2 The structure of a DNA molecule—the nucleotide subunits include four types of bases (A, T, G, and C).

DNA: A LIBRARY OF INFORMATION

In some ways, the bases in DNA are like the letters of an alphabet, only the DNA "letters" are chemical letters. Because there are only four letters (A, T, G, and C) in the DNA alphabet, scientists thought that DNA was too simple to contain the complex genetic information of life. But what is also significant in DNA is the sequence of the letters, not just the letters themselves. Using these four letters in long sequences, nature can create an almost unlimited variety of genetic messages.

When you realize that human DNA consists of three billion pairs of bases, you can begin to imagine how much information can be stored in the DNA of our cells. All of the information for constructing our bodies, determining all of our characteristics or traits, and keeping our bodies functioning is stored in the linear sequences of bases in our DNA. The same is true for all other organisms on Earth. The evolutionary relationship between two organisms can be learned by comparing their DNA. The more similar their sequences of bases, the more recently the two organisms evolved from a common ancestor. (See Figure 19-4.)

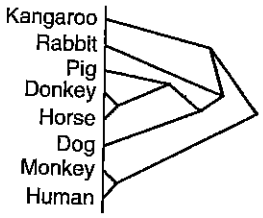


Figure 19-4 Evolutionary relationships are confirmed by DNA closeness—the more similar their base sequences, the more recently two organisms evolved from a common ancestor. For example, the donkey and the horse are more closely related than are the pig and the horse.

To make use of the genetic information stored in DNA, organisms must change that information into proteins. Proteins are made up of amino acids, subunits that—like nucleotide bases—are joined in a linear sequence. The sequence of DNA subunits is used to direct the synthesis of proteins that have the correct sequence of amino acid subunits. In other words, through a chemical process, the order of the nucleotides determines the order of the amino acids in the proteins that are built.

DNA REPLICATION: PASSING IT ON

To qualify as genetic material, DNA has to be able to **replicate**, or make a copy of, itself. This process of DNA replication occurs during the middle of the cell cycle. What we already know about its structure is enough to explain how DNA replicates.

To make a copy, you need an original, sometimes called a **template**. Because DNA is a double helix, it has templates built into it. To begin the process, the double helix unwinds.

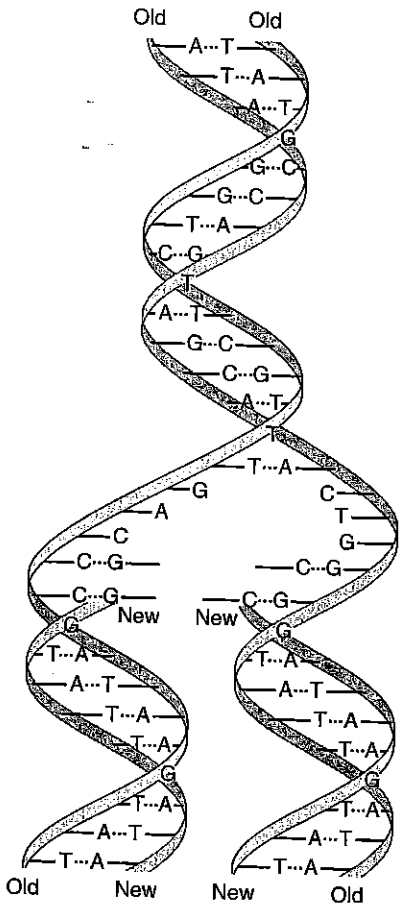


Figure 19-5 During DNA replication, the double helix unwinds, the strands separate, and the new strands form opposite each of the original DNA strands.

As with all metabolic activities, **enzymes** are needed for this process. Once the double-stranded molecule is untwisted, it begins to unzip, just like a zipper. Through the activity of an enzyme, the bonds between bases begin to break apart. (See Figure 19-5.)

As the bonds break, each strand of the DNA molecule becomes separate. Many free subunits float around in the cell. Specific enzymes match up these free subunits with the existing subunits in each DNA strand. Wherever a T is located on a strand, an A pairs to it; wherever a C is located, a G joins up, and so on. One by one, new subunits are joined together to make a new strand opposite each old strand. The sequence of bases in the old strands determines the linear sequence of subunits in the new strands. When replication is complete, two double-stranded DNA molecules are formed. Each molecule is made up of one old strand joined to a newly synthesized

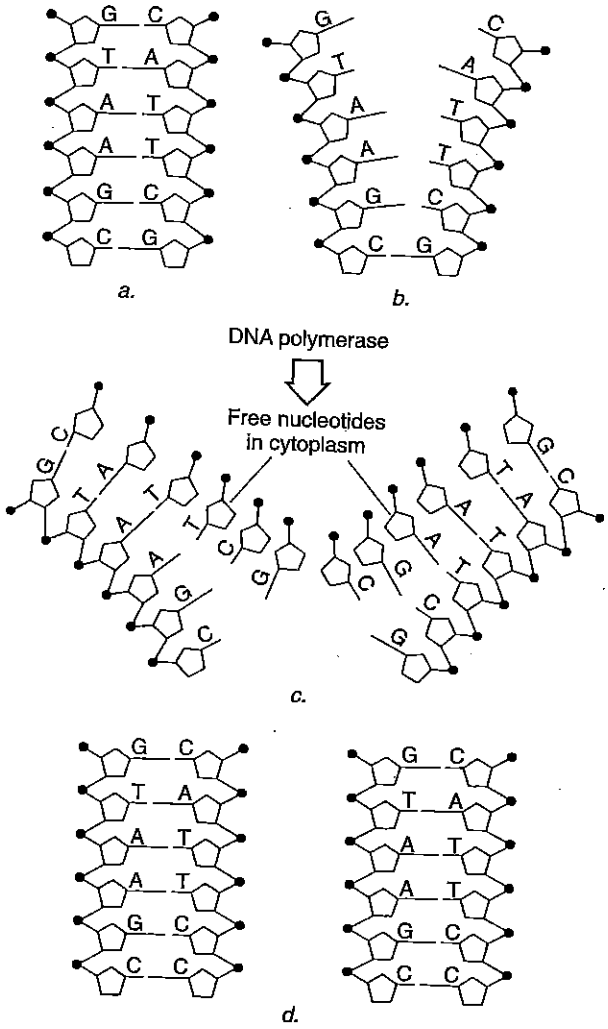


Figure 19-6 Through the process of DNA replication, two identical double-stranded DNA molecules are formed.

strand. How do the two new DNA molecules compare to the original one? They are identical. DNA replication has occurred. (See Figure 19-6.)

ERRORS IN DNA REPLICATION

In life, nothing is perfect. This is true about DNA replication, too. The enzymes responsible for directing the correct pairing of subunits during DNA replication occasionally make mistakes. A nucleotide base may be left out. Or the wrong base may be matched up. Sometimes an extra one is added. These mistakes produce errors in the linear sequence in one strand of the DNA molecule. Such an error is called a genetic **mutation**. From what we know about the replication process, once an error occurs in a DNA strand, it may be copied again and again. Thus, a mutation in the genetic material of one cell can easily be passed on to future cells.

A mutation is simply a change. However, many changes in the genetic material are harmful and may make it impossible for future cells, or even the entire organism, to survive. Other mutations cause an unnoticeable change; rather than harming the organism, the mutation seems to produce no effect. And sometimes a mutation gives the organism a sudden advantage that other similar organisms lack. Not only can mutations in DNA be good, but they are actually an important source of the genetic variation that is necessary for natural selection to occur. Much of the evolution of different life forms on Earth has depended on the chance occurrence of these mutations. (Remember: Only mutations within the DNA of gametes can be passed along to offspring; mutations within the DNA of body cells cannot.)

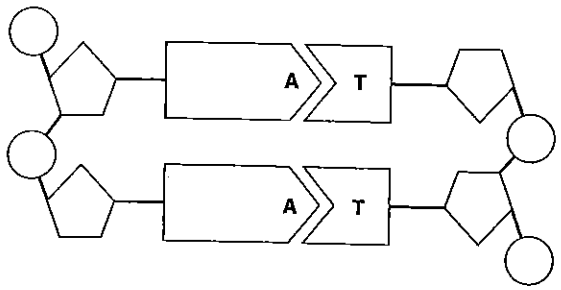
Chapter 19 Review

Part A—Multiple Choice

1. Which is *not* a necessary characteristic of the genetic material?
   1 It must be able to make a copy of itself.
   2 It must be weak so that it can fall apart easily.
   3 It must be able to mutate from time to time.
   4 It must be able to store information.

2. If a set of instructions that determines all of the characteristics of an organism is compared to a book, and a chromosome is compared to a chapter in the book, then what might be compared to a paragraph in the book?
   1 a starch molecule
   2 an amino acid
   3 a protein polymer
   4 a DNA molecule

3. A portion of a molecule is shown in the diagram below. Which statement best describes the main function of this type of molecule?



   1 It is a structural part of the cell wall.
   2 It determines what traits may be inherited.
   3 It stores energy for metabolic processes.
   4 It transports materials across the cell membrane.

4. The subunits of proteins are
   1 simple sugars
   2 phosphates
   3 amino acids
   4 enzymes

5. Watson and Crick contributed to the study of DNA by
   1 experimenting with pea plants
   2 recognizing that traits are inherited
   3 discovering the double helix structure of DNA
   4 mapping the entire human genome

6. The genetic code of a DNA molecule is determined by its specific sequence of
   1 ATP molecules
   2 carbohydrates
   3 sugar molecules
   4 nucleotide bases

7. The DNA molecule is formed from subunits arranged in a
   1 sequence with three kinds of bases
   2 circle with four kinds of bases
   3 sequence with four kinds of bases
   4 sequence with four kinds of acids

8. The base pairs in DNA are similar in arrangement to the
   1 sides of a ladder
   2 steps of a ladder
   3 railing of a staircase
   4 surface of a ramp

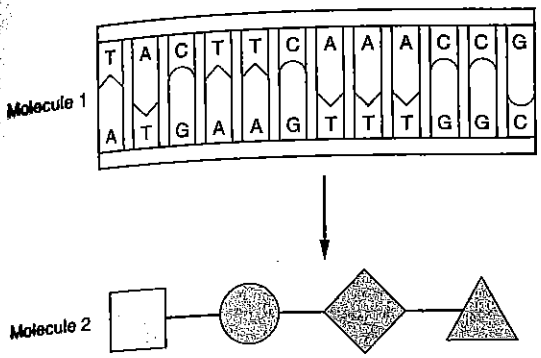
9. The order of the subunits in a strand of DNA is called a
   1 subunit sequence
   2 linear sequence
   3 strand sequence
   4 nucleotide sequence

10. If one strand of a DNA molecule is G-A-T-C-C-A-T, the sequence of the opposite strand is
    1 G-A-T-C-C-A-T
    2 C-T-A-G-G-T-A
    3 A-T-G-G-A-T-G
    4 T-A-C-C-T-A-G

11. The organization of bases in DNA can best be likened to the
    1 arrangement of letters in a word
    2 kinds of tools in a garage
    3 number of books in a library
    4 colors in a rainbow

12. When DNA separates into two strands, the DNA would most likely be directly involved in
    1 replication
    2 differentiation
    3 fertilization
    4 evolution

there is a change in the first three subunits on the upper strand of molecule 1 shown below?



1 The remaining subunits in molecule 1 will also change.
2 Molecule 1 will split apart, triggering an immune response.
3 A portion of molecule 2 may be formed differently.
4 Molecule 2 may form two strands rather than one.

26. In an experiment, DNA from dead pathogenic bacteria was transferred into living bacteria that were, normally, not pathogenic. These altered bacteria were then injected into healthy mice. The mice died of the same disease caused by the original pathogens. Based on this information, which statement would be a valid conclusion?

1 DNA is present only in living organisms.
2 DNA functions only in the original organism from which it comes.
3 DNA changes the organism receiving an injection into another organism.
4 DNA from a dead organism can become active in another organism.

27. Briefly explain how the genetic information is arranged within a DNA molecule.

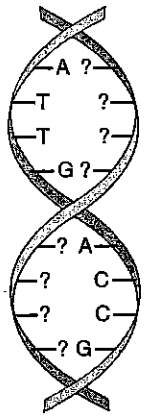
28. You see a photograph of a famous man and his teenaged son. You notice that they look very much alike, and that they even wear similar eyeglasses. What conclusion can you draw from this observation?

1 The DNA present in their body cells is identical.
2 Their percentage of having the same proteins is high.
3 The base sequences of their genes are all identical.
4 The mutation rate is the same in their body cells.

Refer to the figure below to answer questions 29 to 31.

29. The diagram at right represents a molecule of

1 ATP
2 RNA
3 DNA
4 FSH



30. The structures labeled G, C, T, and A all represent

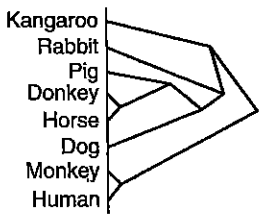
1 acids
2 sugars
3 bases
4 phosphates

31. Starting from the top of the diagram, what would be the letters of the missing units on the matching strand?

32. Complete the analogy: Nucleotide bases are to DNA as amino acids are to

1 sugars
2 proteins
3 lipids
4 nucleic acids

33. Use data from the diagram at right to explain why DNA nucleotide sequencing is important to the study of evolution.



34. How do the nucleotides of the DNA molecule allow it to replicate?

35. Briefly describe the process of DNA replication. Your answer should include the following terms (but not necessarily in this order):

- template
- enzymes
- subunits

Base your answers to questions 36 and 37 on the following chart, which provides information about heredity, and on your knowledge of biology.

20

Genes and Gene Action

GENES AND PROTEINS

Now that it has been shown that DNA is what makes up the genetic material, it is time to look more closely at genes. What is a gene? **Genes** are really packages of information that tell a cell how to make proteins. Proteins are polymers, or long chains, of amino acids. As you learned already, there are 20 different types of amino acids. The order in which the amino acids are joined determines which protein is made. Every different protein has a unique sequence of amino acids. This sequence determines the shape of a protein molecule. It is the shape of the protein that allows the molecule to do its work in the cell.

Genes are specific sections of DNA molecules that are made up of linear sequences of subunits. Proteins are linear sequences of amino acids. How do cells use a linear sequence of subunits in DNA to build a linear sequence of amino acids for a protein? In all cells, except for bacteria, DNA is stored in the nucleus. Yet protein synthesis occurs outside the nuclear membrane, at the **ribosomes**. These small organelles are distributed throughout the cytoplasm. How does the genetic information in DNA within the nucleus get to the ribosomes? A third type of molecule, *ribonucleic acid*, or *RNA*, works as a helper to transfer the information. That is, the genetic information flows from the DNA to the RNA to a protein. (See Figure 20-1.)

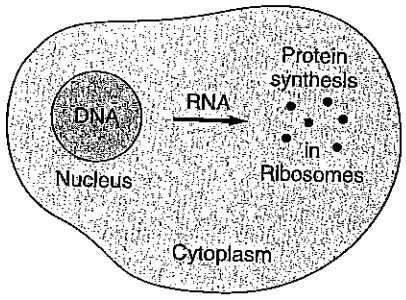


Figure 20-1 The flow of genetic information in a cell—from DNA in the nucleus to RNA to amino acids at the ribosomes.

FROM DNA TO RNA

Each gene is a portion of a chromosome, in effect a portion of the DNA chain. An RNA molecule called *messenger RNA* does the job of moving the information in the base sequence out to the ribosomes. DNA is copied into RNA by a process that is similar to DNA replication. The DNA double helix opens up where a particular gene is located. Special enzymes begin to match up RNA subunits with the correct DNA subunits. The new RNA molecule has the same base sequence as one strand of the original DNA. This RNA molecule then goes out of the nucleus through pores in the nuclear membrane to ribosomes in the cytoplasm. (See Figure 20-2.)

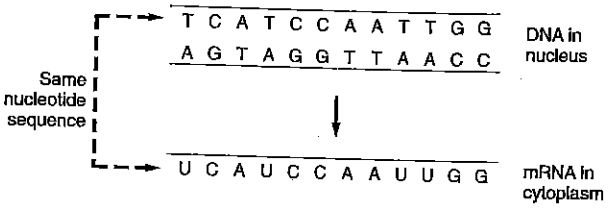


Figure 20-2 The DNA sequence is copied into messenger RNA, which goes out to the ribosomes in the cytoplasm. *Note:* In RNA, the base uracil (U) substitutes for the DNA base thymine (T).

FROM RNA TO PROTEIN

So far, the genetic information, stored as a base sequence, has moved from the nucleus to the cytoplasm by using RNA. Another problem

First Position	Second Position U	Second Position C	Second Position A	Second Position G	Third Position
U	UUU, UUC } Phe; UUA, UUG } Leu	UCU, UCC, UCA, UCG } Ser	UAU, UAC } Tyr; UAA *Stop*; UAG *Stop*	UGU, UGC } Cys; UGA *Stop*; UGG Trp	U C A G
C	CUU, CUC, CUA, CUG } Leu	CCU, CCC, CCA, CCG } Pro	CAU, CAC } His; CAA, CAG } Gln	CGU, CGC, CGA, CGG } Arg	U C A G
A	AUU, AUC, AUA } Ile; AUG Met	ACU, ACC, ACA, ACG } Thr	AAU, AAC } Asn; AAA, AAG } Lys	AGU, AGC } Ser; AGA, AGG } Arg	U C A G
G	GUU, GUC, GUA, GUG } Val	GCU, GCC, GCA, GCG } Ala	GAU, GAC } Asp; GAA, GAG } Glu	GGU, GGC, GGA, GGG } Gly	U C A G

Figure 20-3 The amino acid triplet codes. Note that most amino acids are represented by more than one codon.

remains: how to use the nucleotide base sequence in the RNA to build a protein with the correct sequence of amino acids. This problem involves a change of "language," from the base sequence language of RNA into the amino acid language of proteins. This process is called **translation**, and it occurs at the ribosome.

Built into every living cell in the world is a genetic **code**. It is called the *triplet code*. Each different combination of three bases makes up a word, called a *codon*. Each codon represents a specific amino acid. Each of the 20 amino acids has at least one codon, and most have more than one. This genetic code is universal; in other words, all organisms on Earth use the same genetic code. For example, the codon GCA stands for the amino acid alanine in all life-forms, from bacteria to trees to humans. This similarity among living things is good evidence that all organisms evolved from a common ancestral life-form in Earth's distant past. (See Figure 20-3.)

MUTATIONS: A CLOSER LOOK

In Chapter 19, a mutation was defined as a change in the base sequence of a DNA molecule. The possible effects of a mutation can now be explained in terms of what you know about protein synthesis.

The order of bases in DNA determines the order of amino acids in proteins. In certain cases, a mutation in one subunit will change the triplet code, which in turn may make a change in an amino acid. If this change occurs in a body cell, then all other cells in the organism's body that reproduced (through mitosis) from that cell will have the same change. It is more important, however, if the mutation occurs in the DNA of a gamete. If that gamete fuses with another gamete in sexual reproduction, then the mutation will be inherited. The change in the DNA will be passed on to succeeding generations. The new organism will have the mutation, as will all offspring of that organism. This will be an inherited condition. If the mutation is harmful, the individual and its offspring will have a genetic disease.

GENE EXPRESSION AND CELL DIFFERENTIATION

Chromosomes contain extremely long DNA molecules. Many genes are stretched out along these molecules. For example, it is estimated that there are 20,000 to 30,000 different genes in human cells. After fertilization, every cell of a growing organism arises from the mitotic cell division of other cells. Through mitosis, every cell in our body has the same 46

chromosomes with the same DNA as the original fertilized egg cell.

You learned in Chapter 18 that there are different types of cells in our bodies. We have skin cells, muscle cells, bone cells, nerve cells, blood cells, and so on. If all of these cells have the same DNA, why are they so different from each other? The answer is that only certain genes are used in certain cells. The use of specific information from a gene is called gene **expression**. Proteins are synthesized only from genes that are being expressed, or "turned on." All other genes in the cell are kept silent, or "turned off." This gives the cell its own structure, enzymes, functions, and physical characteristics. A muscle cell contracts, a nerve cell transmits an impulse, and a skin cell helps form a flat, protective layer. The process by which special types of cells are formed through controlled gene expression is called cell **differentiation**. This is an essential process of life. Without cell differentiation, we could not survive, because our bodies would be made up of only one type of cell. While the exact process is not known for certain, it is thought that environmental factors—both outside and inside each cell—influence gene expression. (See Figure 20-4.)

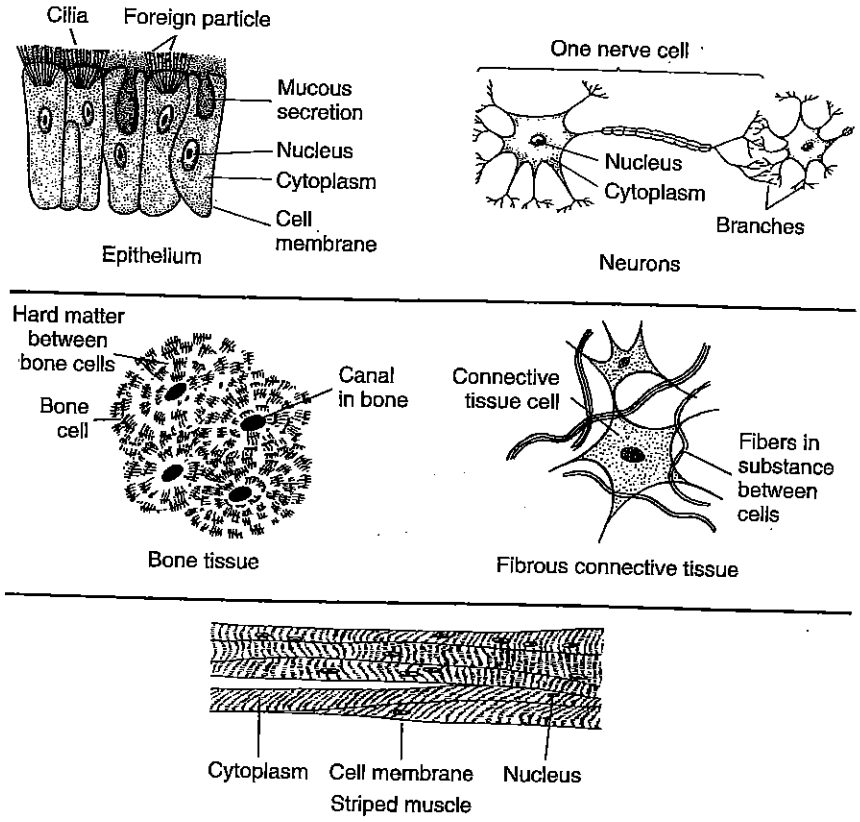


Figure 20-4 Many different types of cells make up the human body. This cell differentiation results from differences in gene expression—only some genes are "turned on" to make the specific proteins needed for each cell type.

Chapter 20 Review

Part A—Multiple Choice

1. Genes can best be described as
1 directions for making DNA
2 directions for making proteins
3 subunits of proteins
4 molecules that transfer information out of the nucleus

2. Which path correctly describes the flow of information in cells?
1 DNA → RNA → protein
2 protein → RNA → DNA
3 protein → DNA → RNA
4 RNA → DNA → protein

3. The kinds of genes that an organism has is determined by the
1 type of amino acids in its cells
2 size of simple sugar molecules in its organs
3 sequence of the subunits A, T, C, and G in its DNA
4 shape of the protein molecules in its organelles

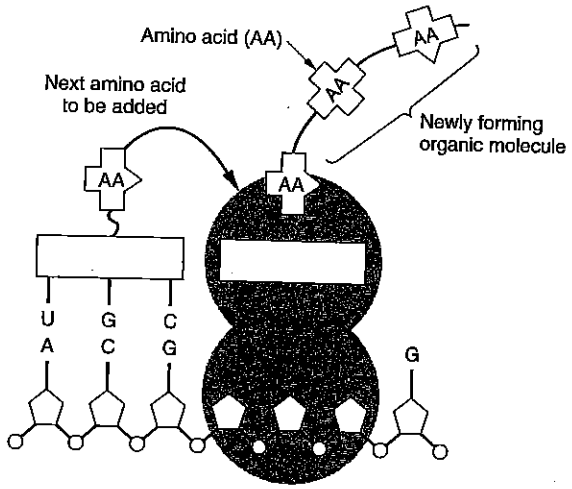
4. A change in the order of DNA bases that code for a respiratory protein will most likely cause
1 the production of a starch that has a similar function
2 a change in the sequence of amino acids determined by the gene
3 the digestion of the altered gene by enzymes
4 the release of antibodies by certain cells to correct the error

5. The role of messenger RNA is to
1 prevent mutations during DNA replications
2 match ribose-containing subunits to subunits of DNA
3 move the information in a base sequence out to the ribosomes
4 translate the base sequence at the ribosomes

6. RNA receives information from DNA by
1 binding with a double helix as a third strand
2 matching with subunits of a single strand of DNA
3 making an exact copy of the DNA molecule
4 accepting proteins through pores in the nuclear membrane

7. What happens at the ribosome?
1 The DNA strands separate.
2 RNA matches up with DNA strands.
3 Genetic information is mutated.
4 RNA is translated into amino acids.

8. The diagram below represents a process that occurs within a cell in the human pancreas. This process is known as



1 digestion by enzymes
2 energy production
3 protein synthesis
4 replication of DNA

9. How many bases make up a codon?
1 one
2 two
3 three
4 four

10. What does a codon represent?
1 a specific amino acid
2 a specific base
3 an RNA molecule
4 an enzyme

11. The genetic code is
1 different for every organism
2 the same for all organisms
3 constantly changing
4 impossible to identify

10

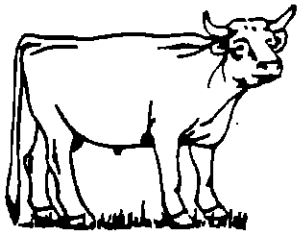
Name _____ Date _____ Class _____

HOW THE GENETIC MESSAGE CHANGES

In your textbook, read about breeding of plants and animals and splicing genes between organisms in Section 28:2.

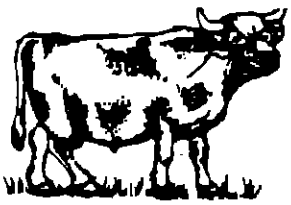
5. This diagram shows two bulls. Below each is a description of that bull's traits.

Bull A



Sleek, clean, solid-colored fur
Long tail, long legs
Milk production of his offspring is low.

Bull B



Rough, spotted fur
Short tail, short legs
Milk production of his offspring is high.

a. Which bull would you choose to breed with a cow to produce a herd of cows that would supply a lot of milk? _____ Why? _____

b. Which bull would you choose for breeding to produce "beautiful" offspring? _____ Why?

_____

c. Which bull would you choose for breeding to produce offspring that would not jump over fences? _____ Why? _____

d. Explain the value of plant and animal breeding. _____

_____

_____

6. What is recombinant DNA? _____

_____

7. Why does gene splicing work? _____

_____

8. List four ways that gene splicing is of value to humans now or may be of value in the future.

_____

_____

_____

RNA differs from DNA because: 1. 2.	These can be positive, negative or have no effect	DNA is the code responsible for making _____ that determine your traits	Missing a base is a _____ mutation	Nitrogen bases have _____ bonds
Mutations can sometimes be fixed by	This number of nucleotides make(s) up a codon:	Variation in species is due to the order or sequence of	Having the wrong bases pair up is a _____ mutation	A ladder does not show the _____ shape of DNA
Inserting a gene to make insulin into a bacterium is an example of	Ribosomes are found in a cell's	The building blocks of proteins are	Each replicated DNA has one old and _____ strand	This molecule determines genotypes and phenotypes
Mating 2 organisms with desirable traits is called	DNA is found in a cell's	The building blocks of DNA are	Beads as nitrogen bases don't show that the bases are two different_____	Having this makes copying something more accurate
To be passed on to offspring, mutations must be in a	Proteins that help reactions take place are called	Nitrogen bases are found in _____ pairs	Nitrogen bases in your DNA model were represented by	A kind of DNA passed from the mother only

*Name:*_____

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The Expression of Genetic Information p. 521

- Gene expression is the process _____

  _____

- Genes have the information to build proteins. Proteins carry out critical _____

  _____. The proteins that are made from genes not only give an organism all of their features (their phenotypes), but also are responsible for carrying out all of the processes that take place in the organism.

- The protein that is expressed is determined by _____

  _____. DNA makes proteins based on what the order those bases are in.

  - Proteins are made of smaller units called amino acids.
  - The order of the bases on DNA are responsible _____

    _____

- How does this process of making proteins happen?

1. Transcription occurs first, where a molecule of RNA is made from the DNA.
   - RNA looks just like DNA, but it is single stranded, has the sugar _____ and U-uracil replaces the T's.
2. The RNA molecule is made when enzymes unzip the DNA and one side is _____

   _____
3. There are three types of RNA that are made from DNA:
   - mRNA-_____

     _____

     _____
   - tRNA-_____

     _____
   - rRNA- _____

     _____

Translating the Message In mRNA p.524

- After the mRNA is made it will act like a blueprint for the making of the protein.
- Translation is the process where the mRNA _____

_____

_____

- Proteins are built from 20 different amino acids. The tRNA molecule is responsible for _____

_____

- The mRNA molecule moves through the ribosome and every three bases on the mRNA, _____ _____, is matched up with a complementary section on a tRNA molecule, called _____ _____. When this matching occurs, the tRNA drops off the correct amino acid, and it is added to the growing protein chain.

Manipulating Genetic Material p.530

- In the past 40 years, science has greatly increased our understanding of the structure and function of our genetic information and how we work with it in the lab.
- Genetic engineering is the process of _____

_____

  - Selective breeding is a type of engineering in that _____

_____

_____

- In recent years, scientists have developed new techniques for examining genetic information.
- These techniques make it possible to change the genotypes of organisms, which couldn't be done with selective breeding.
- Recombinant DNA is _____

_____

_____

- Read the scenario about the cotton plant and bollworms on page 531.
- How did the geneticists make the cotton plant resistant to the bollworm? _____

_____

_____

_____

- A transgenic organism is a _____

_____

- How are researchers now able to make large amounts of insulin in a lab for people who have diabetes? _____

_____

_____

- Gene therapy is when _____ are put human body for the purpose of _____.
  - This has only been successful in the last 20 years.