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# Genes and Chromosomes

*By **David N. Finegold** , MD, University of Pittsburgh*

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**Genes are segments of deoxyribonucleic acid (DNA) that contain the code for a specific protein that functions in one or more types of cells in the body. Chromosomes are structures within cells that contain a person's genes.**

- Genes are contained in chromosomes, which are in the cell nucleus.
- A chromosome contains hundreds to thousands of genes.
- Every normal human cell contains 23 pairs of chromosomes, for a total of 46 chromosomes.
- A trait is any gene-determined characteristic and is often determined by more than one gene.
- Some traits are caused by mutated genes that are inherited or that are the result of a new gene mutation.

Proteins are probably the most important class of material in the body. Proteins are not just building blocks for muscles, connective tissues, skin, and other structures. They also are needed to make enzymes. Enzymes are complex proteins that control and carry out nearly all chemical processes and reactions within the body. The body produces thousands of different enzymes. Thus, the entire structure and function of the body is governed by the types and amounts of proteins the body synthesizes. Protein synthesis is controlled by genes, which are contained on chromosomes.

The **genotype** (or genome) is a person's unique combination of genes or genetic makeup. Thus, the genotype is a complete set of instructions on how that person's body synthesizes proteins and thus how that body is *supposed* to be built and function.

The **phenotype** is the *actual* structure and function of a person's body. The phenotype is how the genotype manifests in a person—not all the instructions in the genotype may be carried out (or expressed). Whether and how a gene is expressed is determined not only by the genotype but also by the environment (including illnesses and diet) and other factors, some of which are unknown.

A **karyotype** is a picture of the full set of chromosomes in a person's cells.

## Genes

Humans have about 20,000 to 23,000 genes.

### DNA

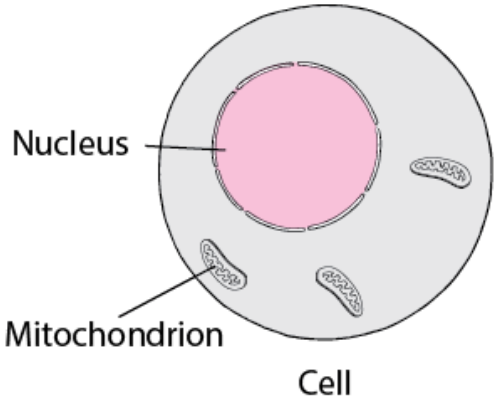
Genes consist of deoxyribonucleic acid (DNA). DNA contains the code, or blueprint, used to synthesize a protein. Genes vary in size, depending on the sizes of the proteins for which they code. Each DNA molecule is a long double helix that resembles a spiral staircase containing millions of steps. The steps of the staircase consist of pairs of four types of molecules called bases (nucleotides). In each step, the base adenine (A) is paired with the base thymine (T), or the base guanine (G) is paired with the base cytosine (C). Each extremely long DNA molecule is coiled up inside one of the chromosomes.

## Structure of DNA

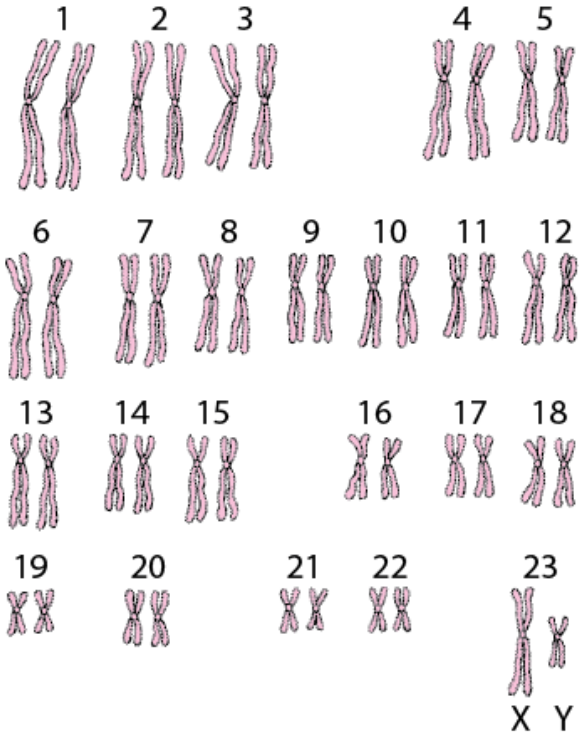
DNA (deoxyribonucleic acid) is the cell's genetic material, contained in chromosomes within the cell nucleus and mitochondria.

Except for certain cells (for example, sperm and egg cells and red blood cells), the cell nucleus normally contains 23 pairs of chromosomes. A chromosome contains many genes. A gene is a segment of DNA that provides the code to construct a protein.

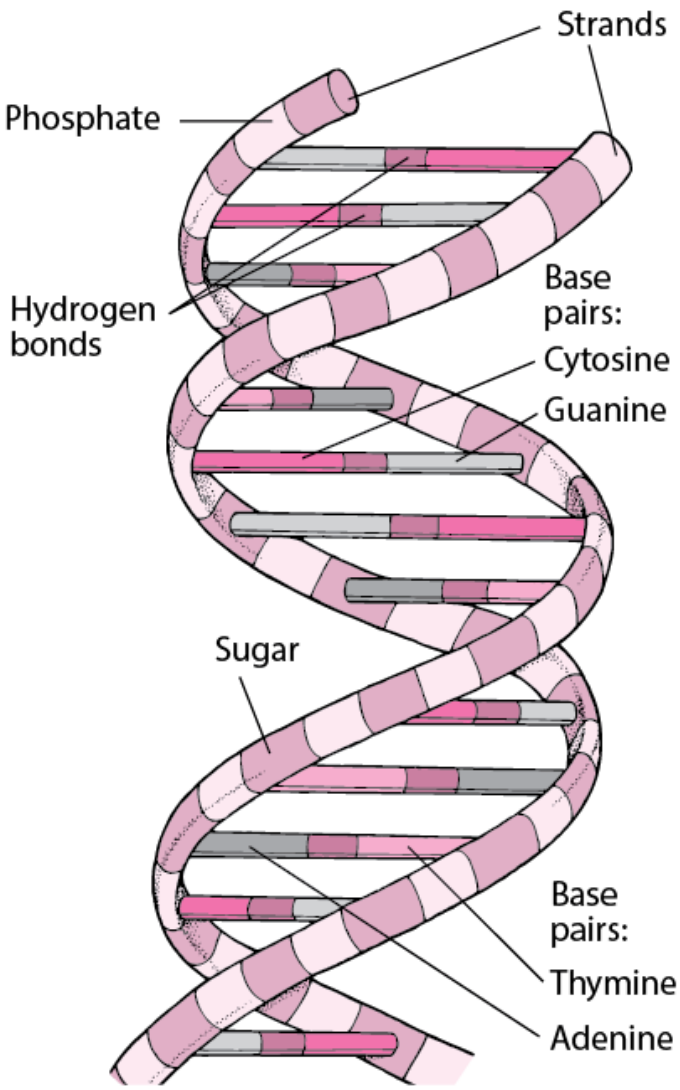
The DNA molecule is a long, coiled double helix that resembles a spiral staircase. In it, two strands, composed of sugar (deoxyribose) and phosphate molecules, are connected by pairs of four molecules called bases, which form the steps of the staircase. In the steps, adenine is paired with thymine and guanine is paired with cytosine. Each pair of bases is held together by a hydrogen bond. A gene consists of a sequence of bases. Sequences of three bases code for an amino acid (amino acids are the building blocks of proteins) or other information.



Cell



Pairs of Chromosomes in a Human Cell



DNA Double Helix

## Synthesizing proteins

Proteins are composed of a long chain of amino acids linked together one after another. There are 20 different amino acids that can be used in protein synthesis—some must come from the diet (essential amino acids), and some are made by enzymes in the body. As a chain of amino acids is put together, it folds upon itself to create a complex three-dimensional

structure. It is the shape of the folded structure that determines its function in the body. Because the folding is determined by the precise sequence of amino acids, each different sequence results in a different protein. Some proteins (such as hemoglobin) contain several different folded chains. Instructions for synthesizing proteins are coded within the DNA.

## Coding

Information is coded within DNA by the sequence in which the bases (A, T, G, and C) are arranged. The code is written in triplets. That is, the bases are arranged in groups of three. Particular sequences of three bases in DNA code for specific instructions, such as the addition of one amino acid to a chain. For example, GCT (guanine, cytosine, thymine) codes for the addition of the amino acid alanine, and GTT (guanine, thymine, thymine) codes for the addition of the amino acid valine. Thus, the sequence of amino acids in a protein is determined by the order of triplet base pairs in the gene for that protein on the DNA molecule. The process of turning coded genetic information into a protein involves transcription and translation.

## Transcription and translation

**Transcription** is the process in which information coded in DNA is transferred (transcribed) to ribonucleic acid (RNA). RNA is a long chain of bases just like a strand of DNA, except that the base uracil (U) replaces the base thymine (T). Thus, RNA contains triplet-coded information just like DNA.

When transcription is initiated, part of the DNA double helix opens and unwinds. One of the unwound strands of DNA acts as a template against which a complementary strand of RNA forms. The complementary strand of RNA is called messenger RNA (mRNA). The mRNA separates from the DNA, leaves the nucleus, and travels into the cell cytoplasm (the part of the cell outside the nucleus—see Figure: Inside a Cell). There, the mRNA attaches to a ribosome, which is a tiny structure in the cell where protein synthesis occurs.

With **translation,** the mRNA code (from the DNA) tells the ribosome the order and type of amino acids to link together. The amino acids are brought to the ribosome by a much smaller type of RNA called transfer RNA (tRNA). Each molecule of tRNA brings one amino acid to be incorporated into the growing chain of protein, which is folded into a complex three-dimensional structure under the influence of nearby molecules called chaperone molecules.

## Control of gene expression

There are many types of cells in a person's body, such as heart cells, liver cells, and muscle cells. These cells look and act differently and produce very different chemical substances. However, every cell is the descendant of a single fertilized egg cell and as such contains essentially the same DNA. Cells acquire their very different appearances and functions because different genes are expressed in different cells (and at different times in the same cell). The information about when a gene should be expressed is also coded in the DNA. Gene expression depends on the type of tissue, the age of the person, the presence of specific chemical signals, and numerous other factors and mechanisms. Knowledge of these other factors and mechanisms that control gene expression is growing rapidly, but many of these factors and mechanisms are still poorly understood.

The mechanisms by which genes control each other are very complicated. Genes have chemical markers to indicate where transcription should begin and end. Various chemical substances (such as histones) in and around the DNA block or permit transcription. Also, a strand of RNA called antisense RNA can pair with a complementary strand of mRNA and block translation.

## Replication

Cells reproduce by dividing in two. Because each new cell requires a complete set of DNA molecules, the DNA molecules in the original cell must reproduce (replicate) themselves during cell division. Replication happens in a manner similar to transcription, except that the entire double-strand DNA molecule unwinds and splits in two. After splitting, bases on each strand bind to complementary bases (A with T, and G with C) floating nearby. When this process is complete, two identical double-strand DNA molecules exist.

## Mutation

To prevent mistakes during replication, cells have a "proofreading" function to help ensure that bases are paired properly. There are also chemical mechanisms to repair DNA that was not copied properly. However, because of the billions of base pairs involved in, and the complexity of, the protein synthesis process, mistakes may happen. Such mistakes may occur for numerous reasons (including exposure to radiation, drugs, or viruses) or for no apparent reason. Minor variations in DNA are very common and occur in most people. Most variations do not affect subsequent copies of the gene. Mistakes that are duplicated in subsequent copies are called mutations.

**Inherited mutations** are those that may be passed on to offspring. Mutations can be inherited only when they affect the reproductive cells (sperm or egg). Mutations that do not affect reproductive cells affect the descendants of the mutated cell (for example, becoming a cancer) but are not passed on to offspring.

Mutations may be unique to an individual or family, and most harmful mutations are rare. Mutations that become so common that they affect more than 1% of a population are called polymorphisms (for example, the human blood types A, B, AB, and O). Most polymorphisms have little or no effect on the phenotype (the *actual* structure and function of a person's body).

Mutations may involve small or large segments of DNA. Depending on its size and location, the mutation may have no apparent effect or it may alter the amino acid sequence in a protein or decrease the amount of protein produced. If the protein has a different amino acid sequence, it may function differently or not at all. An absent or nonfunctioning protein is often harmful or fatal. For example, in phenylketonuria, a mutation results in the deficiency or absence of the enzyme phenylalanine hydroxylase. This deficiency allows the amino acid phenylalanine (absorbed from the diet) to accumulate in the body, ultimately causing severe intellectual disability. In rare cases, a mutation introduces a change that is advantageous. For example, in the case of the sickle cell gene, when a person inherits two copies of the abnormal gene, the person will develop sickle cell disease. However, when a person inherits only one copy of the sickle cell gene (called a carrier), the person develops some protection against malaria (a blood infection). Although the protection against malaria can help a carrier survive, sickle cell disease (in a person who has two copies of the gene) causes symptoms and complications that may shorten life span.

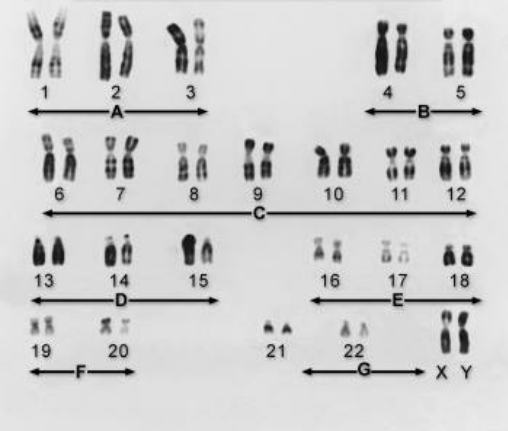
**Natural selection** refers to the concept that mutations that impair survival in a given environment are less likely to be passed on to offspring (and thus become less common in the population), whereas mutations that improve survival progressively become more common. Thus, beneficial mutations, although initially rare, eventually become common. The slow changes that occur over time caused by mutations and natural selection in an interbreeding population collectively are called **evolution**.

### Did You Know...

Not all gene abnormalities are harmful. For example, the gene that causes sickle cell disease also provides protection against malaria.

## Chromosomes

### Chromosomes

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A chromosome is made of a very long strand of DNA and contains many genes (hundreds to thousands). The genes on each chromosome are arranged in a particular sequence, and each gene has a particular location on the chromosome (called its locus). In addition to DNA, chromosomes contain other chemical components that influence gene function.

## Pairing

Except for certain cells (for example, sperm and egg cells or red blood cells), the nucleus of every normal human cell contains 23 pairs of chromosomes, for a total of 46 chromosomes. Normally, each pair consists of one chromosome from the mother and one from the father.

There are 22 pairs of nonsex (autosomal) chromosomes and one pair of sex chromosomes. Paired nonsex chromosomes are, for practical purposes, identical in size, shape, and position and number of genes. Because each member of a pair of nonsex chromosomes contains one of each corresponding gene, there is in a sense a backup for the genes on those chromosomes.

The 23rd pair is the sex chromosomes (X and Y).

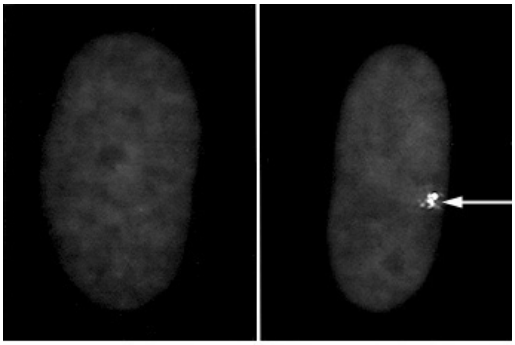
## Sex chromosomes

The pair of sex chromosomes determines whether a fetus becomes male or female. Males have one X and one Y chromosome. A male's X comes from his mother and the Y comes from his father. Females have two X chromosomes, one from the mother and one from the father. In certain ways, sex chromosomes function differently than nonsex chromosomes.

The smaller Y chromosome carries the genes that determine male sex as well as a few other genes. The X chromosome contains many more genes than the Y chromosome, many of which have functions besides determining sex and have no counterpart on the Y chromosome. In males, because there is no second X chromosome, these extra genes on the X chromosome are not paired and virtually all of them are expressed. Genes on the X chromosome are referred to as sex-linked, or X-linked, genes.

Normally, in the nonsex chromosomes, the genes on both of the pairs of chromosomes are capable of being fully expressed. However, in females, most of the genes on one of the two X chromosomes are turned off through a process called X inactivation (except in the eggs in the ovaries). X inactivation occurs early in the life of the fetus. In some cells, the X from the father becomes inactive, and in other cells, the X from the mother becomes inactive. Thus, one cell may have a gene from the person's mother and another cell has the gene from the person's father. Because of X inactivation, the absence of one X chromosome usually results in relatively minor abnormalities (such as Turner syndrome). Thus, missing an X chromosome is far less harmful than missing a nonsex chromosome (see Overview of Sex Chromosome Abnormalities).

### Inactive X Chromosome

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If a female has a disorder in which she has more than two X chromosomes, the extra chromosomes tend to be inactive. Thus, having one or more extra X chromosomes causes far fewer developmental abnormalities than having one or more extra nonsex chromosomes. For example, women with three X chromosomes (triple X syndrome) are often physically and mentally normal. Males who have more than one Y chromosome (see XYY Syndrome) may have physical and mental abnormalities.

## Chromosome abnormalities

There are several types of chromosome abnormalities. A person may have an abnormal number of chromosomes or have abnormal areas on one or more chromosomes. Many such abnormalities can be diagnosed before birth (see Testing for

chromosome and gene abnormalities).
Abnormal numbers of nonsex chromosomes usually result in severe abnormalities. For example, receiving an extra nonsex chromosome may be fatal to a fetus or lead to abnormalities such as Down syndrome, which commonly results from a person having three copies of chromosome 21. Absence of a nonsex chromosome is fatal to the fetus.
Large areas on a chromosome may be abnormal, usually because a whole section was left out (called a deletion) or mistakenly placed in another chromosome (called translocation). For example, chronic myelogenous leukemia is sometimes caused by translocation of part of chromosome 9 onto chromosome 22. This abnormality can be inherited or be the result of a new mutation.

### Mitochondrial chromosomes

Mitochondria are tiny structures inside cells that synthesize molecules used for energy. Unlike other structures inside cells, each mitochondrion contains its own circular chromosome. This chromosome contains DNA (mitochondrial DNA) that codes for some, but not all, of the proteins that make up that mitochondrion. Mitochondrial DNA usually comes only from the person's mother because, in general, when an egg is fertilized, only mitochondria from the egg become part of the developing embryo. Mitochondria from the sperm usually do not become part of the developing embryo.

## Traits

A trait is any gene-determined characteristic. Many traits are determined by the function of more than one gene. For example, a person's height is likely to be determined by many genes, including those affecting growth, appetite, muscle mass, and activity level. However, some traits are determined by the function of a single gene.
Variation in some traits, such as eye color or blood type, is considered normal. Other variations, such as albinism, Marfan syndrome, and Huntington disease, harm body structure or function and are considered disorders. However, not all such gene abnormalities are uniformly harmful. For example, one copy of the sickle cell gene can provide protection against malaria, but two copies of the gene cause sickle cell anemia.

## Genetic Disorders

A genetic disorder is a detrimental trait caused by an abnormal gene. The abnormal gene may be inherited or may arise spontaneously as a result of a new mutation. Gene abnormalities are fairly common. Humans carry an average of 100 to 400 abnormal genes. However, most of the time the corresponding gene on the other chromosome in the pair is normal and prevents any harmful effects. In the general population, the chance of a person having two copies of the same abnormal gene (and hence a disorder) is very small. However, in children who are offspring of close blood relatives, the chances are higher. Chances are also higher among children of parents who have married within an isolated population, such as the Amish or Mennonites.

### Did You Know...

People carry an average of 100 to 400 abnormal genes.