THE MOLECULAR BASIS OF LIFE: DNA: THE DOUBLE HELIX

Cells are the fundamental units of living things; they are like miniature machines or tiny chemical factories that arrange molecules into living matter. Most plants and animals are made up of millions of cells, each specialized for its own particular role: red blood cells carry oxygen; nerve cells conduct electrical impulses; and the cells lining the stomach secrete digestive enzymes. All cells have a full set of the genetic information that directs all the processes of life: growth, development, and metabolism. This genetic information, passed from parent to child, is carried in code in the molecule called *d*eoxyribo*n*ucleic *a*cid or DNA. The DNA, which directs the construction of molecules necessary for cellular function, codes for genetic information and is identical in all living organisms, indicating a common origin for all life on earth.

Begin in the upper right-hand corner and color each picture as it is mentioned in the text. First color the cell membrane, the structure that encloses and protects the cell's components and controls what leaves and enters the cell. Color all the components of the cell.

Here we picture a typical eukaryotic or nucleated cell. In eukaryotic cells, the DNA is found in packages called *chromosomes,* located within the nucleus, which is surrounded by the *nuclear envelope.* (In prokaryotic cells, which lack a nucleus, the DNA is located in the *cytoplasm.*)

Notice also the *nucleolus,* a nuclear organelle that produces ribosomes. (We will come across ribosomes again in Plate 22.) The porous nuclear membrane allows the selective exchange of molecules between the nucleus and *cytoplasm;* it remains intact as long as the cell is not dividing.

Color the enlarged chromosome to the left of the cell.

Most of the time, the DNA in the nucleus resembles a loosely tangled mass and distinct *chromosomes* cannot be detected. When the cell prepares to divide (in prophase), the DNA duplicates and forms two duplicate *chromosomes* joined by a *centromere.* Each duplicate *chromosome* is called a *sister chromatid.* Distinct *chromosomes* can be seen under the microscope.

If you move to a greater level of magnification, you can see the helical shape of the DNA molecule. It is a *double helix,* looking somewhat like a twisted ladder. The ladder is composed of *strand 1* and *strand 2,* twisted in opposite directions around one another.

Color the magnified double helix. Color each strand of the large helix on the left.

The backbones of these two strands are held together by the *base pair* "rungs."

Begin with the top rung and color all the base pairs that occur between the strands or backbone. Color the hydrogen bonds as well.

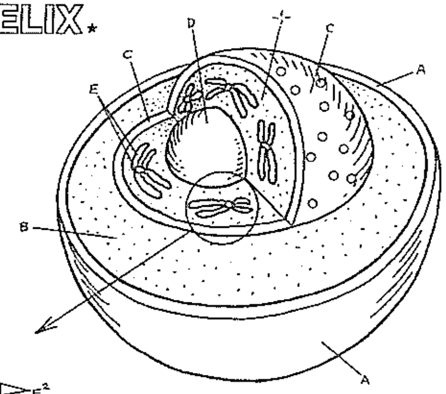
A *base pair* is formed by two nucleotide bases attached to one another by the partial charges of *hydrogen bonds.* (The structure of DNA will be more fully explained in Plate 21.) A single *hydrogen bond* is weak, but the multiple bonds down the rungs of the DNA molecule make it very strong. The multiple bonds also give the DNA molecule the capacity to open and close like a zipper, which is important for replication.

As the master controller of the cell, DNA controls its own replication and governs the synthesis of structural proteins, out of which our bodies are built. It governs the production of enzymes needed for the control of the thousands of chemical reactions that occur in the cell and contains the complete instructions for making a new organism.

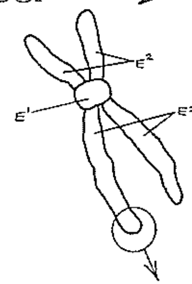
The DNA *double helix* structure was discovered in 1953 by Francis Crick and James Watson. Along with Maurice Wilkins, they won the Nobel Prize for physiology and medicine in 1962. The story of this exciting discovery is told in Watson's *The Double Helix.* Once the structure of DNA was known, it became possible to unravel further secrets of the hereditary material: how it replicates itself, how it finds its way from one generation to the next, and how the information recorded on the *double helix* is "read" within the cell.

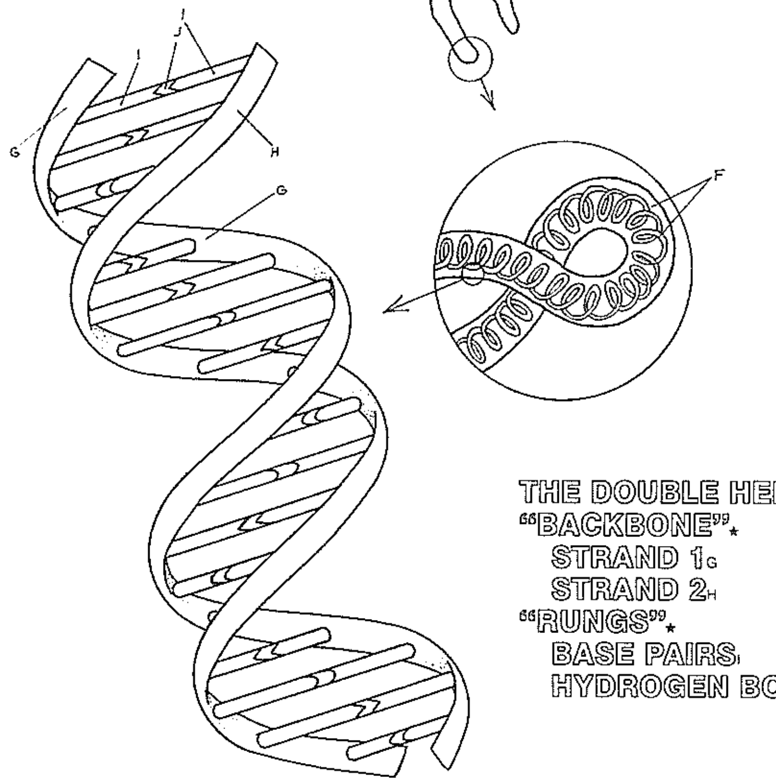
DNA: THE DOUBLE HELIX *

LOCATION IN CELL •
CELL MEMBRANE A
CYTOPLASM B
NUCLEAR ENVELOPE C
NUCLEOLUS D
CHROMOSOMES E
CENTROMERE E¹
SISTER CHROMATIDS E²



CELL AT PROPHASE





THE DOUBLE HELIX F
"BACKBONE" *
STRAND 1 G
STRAND 2 H
"RUNGS" *
BASE PAIRS I
HYDROGEN BONDS J

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THE MOLECULAR BASIS OF LIFE: DNA REPLICATION

The unique structure of the DNA double helix allows for the accurate duplication of genetic information coded into the molecule. Each time a cell divides through mitosis (Plate 29), as the organism grows, or in the formation of sex cells through meiosis (Plate 30), each new daughter cell gets an identical copy of the genetic material. This plate shows how this exact duplication of information occurs.

Continue to use the same colors as on the previous plate for G through J. Begin at the top of the plate and color each structure in the first section: parent strand 1, parent strand 2, the base pairs, and the hydrogen bonds holding them together. You have now colored the DNA molecule as it appears prior to replication, in its double helix formation.

Proceed to the middle of the plate and color parent strands 1 and 2 and the bases, where they have pulled apart.

The replication process begins when the two *parent strands* separate, or "unzip," as the *hydrogen bonds* between two *base pairs* are broken in the presence of specific enzymes. The arrows represent each of the *parent strands* pulling apart. The bases are now exposed to the many molecules floating within the nucleus. Some of these molecules are *free nucleotides*.

Color all the free nucleotides that are floating around the DNA strands. All parts of the free nucleotides are colored the same.

A *free nucleotide* is a three-part molecule composed of a *phosphate* (K^1), a *sugar* (K^2), and a *base* (K^3). Each *base* is complementary to the newly separated *bases* in the *parent DNA strands*. The *free nucleotides* and the free ends of the *bases* on the unzipped DNA *parent strands* attract complementary *bases* (see Plate 21), as indicated by the small arrows. *Hydrogen bonds* form. These can be seen at the bottom of the middle section.

At the bottom of the plate you can see that as a *free nucleotide* forms a *hydrogen bond* with a base on the *parent strand*, a new ladder begins to form: the *base pairs* form the "rungs," and the *phosphates* and *sugars* bond to form a new "backbone" for the *daughter strand*.

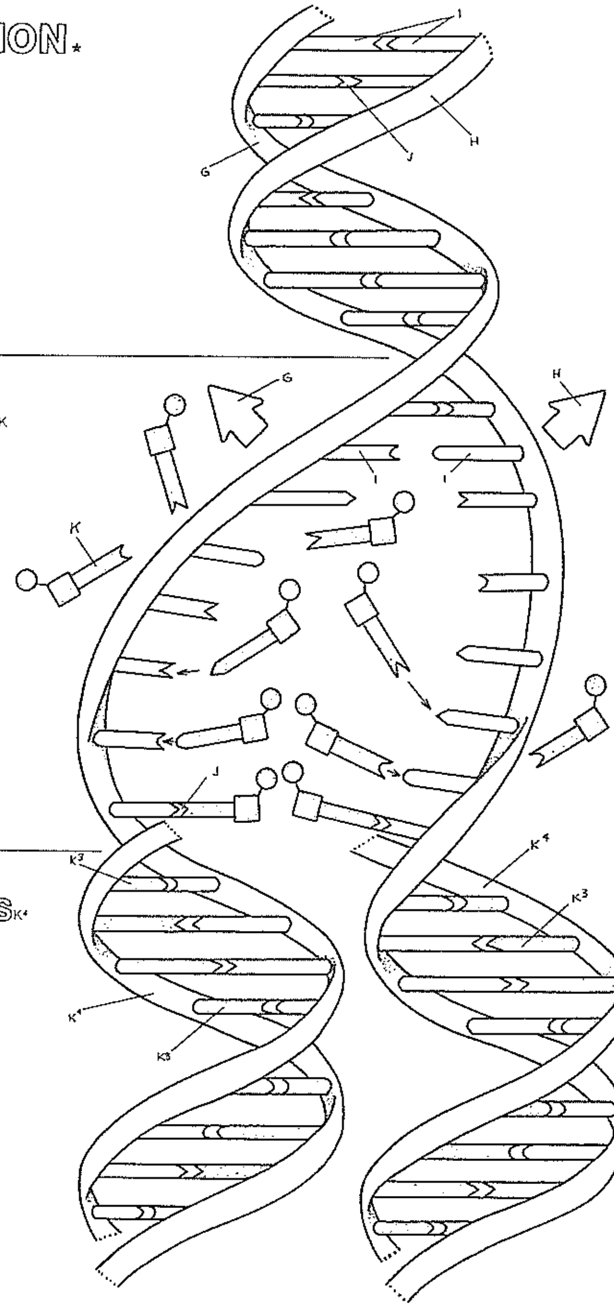
Color the daughter backbone on the diagram to the left. The stippling indicates the actual structure of the molecules. Coloring the entire area gives an indication of the three-dimensional space forming the backbone. Color the rest of the plate.

Replication is finished when a complete *daughter strand* is joined with each *parent strand*, thus forming two new double helices. One intact strand from the parent helix, and one newly synthesized complementary *daughter strand* form each new double helix.

From one DNA molecule, two identical molecules have been formed, each carrying the same genetic information. After the DNA has replicated, the cell is ready to divide into two daughter cells. The accurate duplication and transmission of genetic information from generation to generation is essential. Mistakes in this replication process, called mutations, regularly occur. Many mutations are disadvantageous, although some are neutral or advantageous. The mistakes provide the variation at the genetic level necessary for change and evolution. We will see (in Plates 41 and 42) an example of how a mutation in the human DNA changes a blood protein so that it is advantageous in certain environments.

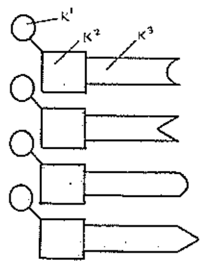
DNA REPLICATION*

PARENT STRAND 1$_G$
PARENT STRAND 2$_H$
BASE PAIRS$_I$
HYDROGEN BONDS$_J$



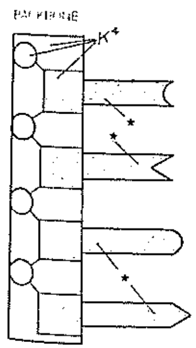
UNZIPPING*

FREE NUCLEOTIDES$_K$
PHOSPHATE$_{K^1}$
SUGAR$_{K^2}$
BASE$_{K^3}$



REPLICATION*

DAUGHTER STRANDS$_{K^4}$



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THE MOLECULAR BASIS OF LIFE: COMPONENTS OF DNA & RNA MOLECULES

We will now look even closer at the molecules that carry all our genetic information. We learned in the previous plate that the *nucleotide* is the fundamental unit of the DNA molecule.

Begin by coloring the dotted line around the single nucleotide on both the molecules located on the DNA and the messenger RNA molecules.

Note again that a *nucleotide* consists of a *phosphate, sugar,* and a *base.*

Color all the components of the DNA molecule on the left, including those within the dotted line.

Notice that the *phosphate* and *sugar* of each *nucleotide* bind to form what we have been calling the *backbone* of strands 1 and 2. Note that the *sugar* of the DNA *backbone* is *deoxyribose,* hence the name *d*eoxyribose *n*ucleic *a*cid.

Color the stippled area (G) gray so that the impression of the three-dimensional phosphate-sugar backbone stands out more clearly.

There are two kinds of bases: *purines* and *pyrimidines,* which are complementary and joined by the *hydrogen bonds.* The *purines* are the "longer" molecules whose ends point outward; the *pyrimidines* are "shorter" and are diagrammed here with notches. (On this part of the plate, they are colored the same.) The notches and points indicate a "lock and key" complementarity.

After you have colored all the components of the DNA molecule, proceed to RNA on the right.

In contrast to DNA, messenger RNA consists of a single strand. Its *nucleotides* consist, as in DNA, of a *phosphate,* a *sugar,* and a *purine* or *pyrimidine base.* The RNA *sugar* is *ribose* rather than *deoxyribose sugar,* which has one less oxygen than *ribose.* Thus, *RNA* stands for *r*ibose *n*ucleic *a*cid.

Using two shades of one color for the purine bases and three shades of another, contrasting color for the pyrimidine bases, color the complementary base pairs at the bottom of the plate. Begin with *DNA.*

As noted on the two previous plates, the rungs of the DNA ladder are formed by complementary base pairs. Note that there are two *purine bases, adenine* and *guanine,* and two *pyrimidine bases, cytosine* and *thymine.* A single rung of the DNA double helix must consist of one *purine* and one *pyrimidine,* never two *purines* or two *pyrimidines.* Again, notice how the ends on each base are shaped so they fit together.

In *DNA, adenine* and *thymine* always go together, as do *guanine* and *cytosine.* During replication (as we saw on the previous plate), the free *nucleotides* conjoin with their complementary *bases* of the parent strand. *Adenine* on the parent strand would attract only a nucleotide containing *thymine,* and vice versa. *Guanine* is always found on the same rung as *cytosine.*

Proceed to color the *RNA.*

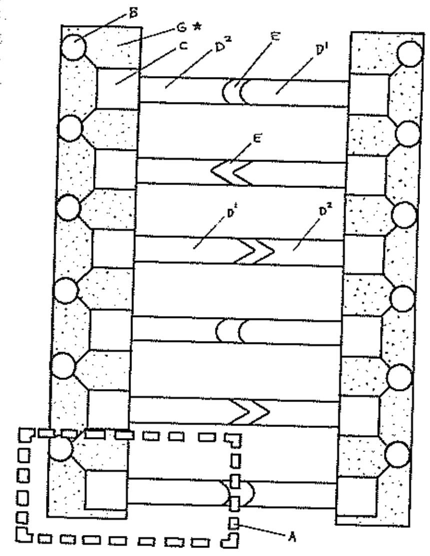
RNA also has four bases, three identical with those of DNA—*adenine, guanine,* and *cytosine.* But the fourth base in RNA is *uracil,* which is chemically very similar to *thymine* (which it replaces). Notice that *uracil* is the same shape as *thymine.* RNA is able to carry the genetic "message" out of the nucleus to the ribosomes in the cytoplasm. The message carried on a single strand of DNA is encoded on the mRNA (messenger RNA) in a complementary fashion. If the base pair on DNA is *guanine,* the mRNA will carry a *cytosine* at that point. For each *adenine* base on the DNA, the mRNA will carry a *uracil.* Remember that in RNA, *thymine* is replaced by the closely related *uracil.*

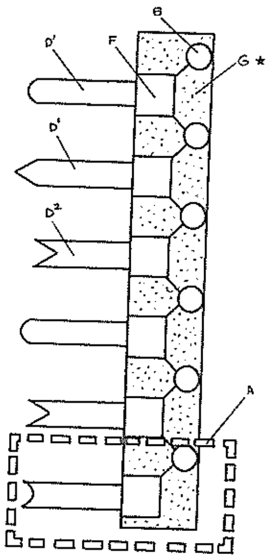
The next plate shows how the messenger RNA relays the information from the nucleus to the cytoplasm—in particular to the ribosomes—where it provides the manufacturing plans for protein production.

COMPONENTS OF DNA & RNA MOLECULES*

NUCLEOTIDE A
DNA •
PHOSPHATE B
SUGAR (DEOXYRIBOSE) C
BASES D ( )
PURINE D¹
PYRIMIDINE D²
HYDROGEN BONDS E

MESSENGER RNA •
PHOSPHATE B
SUGAR (RIBOSE) F
BASES D ( )
PURINE D¹
PYRIMIDINE D²
BACKBONE G*





COMPLEMENTARY BASE PAIRS*

PURINE
BASES D¹
ADENINE H
GUANINE I
PYRIMIDINE
BASES D²
CYTOSINE J
THYMINE K
URACIL L