2-3

THE MOLECULAR BASIS OF LIFE: DNA AND RNA MOLECULES

In the last plate, we saw how the DNA double helix is held together by hydrogen bonds and how it unzips and zips to replicate. In this plate we take a closer look at the smaller units that make up this versatile and essential molecule.

Color the nucleotide at the top of the plate. Note again that a nucleotide consists of a phosphate, a sugar, and a base. Color the components of the DNA double helix. Use two shades of one color for the purine bases and two shades of another, contrasting color for the pyrimidine bases. To aid in recognition of the molecular components, each is labeled with the first letter of its name, for example, nucleotide (n).

Recall that the sides of the ladder or backbones of strands 1 and 2 are alternating phosphate and sugar subunits. The phosphates are all alike, and the deoxyribose sugars are all alike, but the particular sequence of the four bases is different and determines the genetic message of each gene.

The simple alphabet of the DNA "message" consists of four bases A, G, C, and T—adenine, guanine, cytosine, and thymine. The bases are of two chemical types: purines (A and G) and pyrimidines (C and T). One purine is joined to one pyrimidine by hydrogen bonds. Purines are the longer molecules whose ends point outward in the illustration. Pyrimidines are shorter and shown with notches. The notches and points fit together like locks and keys.

Before the structure of DNA was understood, biochemist Erwin Chargaff discovered that any DNA he analyzed always had equal amounts of adenine and thymine, and equal amounts of cytosine and guanine. These equalities, A=T and C=G, known as "Chargaff's Rules," provided a clue to Watson and Crick about DNA structure. The significance of these equalities did not become clear until the double helix was revealed.

The "rungs" of the DNA ladder are either an adenine-thymine (A–T) or a cytosine-guanine (C–G) combination. Note that each combination has one purine (A or G) and one pyrimidine (C or T) and explains Chargaff's Rules. We never observe A–C, A–G, or C–T. We therefore say that A and T are complementary bases, as are C and G.

Color the single DNA strand on the lower left. Then, choose a shade of the pyrimidine color to use for uracil and a new color for ribose. Color the RNA strand and the RNA strands in the cell.

An RNA (ribose nucleic acid) molecule has the sugar subunit ribose (instead of deoxyribose), a phosphate, and four bases. Three bases are identical with those of DNA—namely, adenine, guanine, and cytosine. The fourth RNA base is uracil (U), which is chemically very similar to thymine and also similar in shape.

To get its message out from the nucleus of the cell, DNA makes use of RNA as a courier or messenger. A single strand of DNA makes a "transcript" of itself onto a single strand of RNA as illustrated here. T transcribes an A, but A on the DNA strand transcribes a U instead of a T. G on DNA transcribes a C.

The RNA transcript (called messenger RNA) goes from the nucleus to the cytoplasm. In the cytoplasm, ribosomes eventually "translate" the message into molecules of proteins (2-4).

This complicated information system, which resembles a busy international law office with dictation machines, messengers, transcriptionists, and translators, may have been much simpler in the remote past. Many molecular biologists now think that an "RNA world" preceded the present DNA world as life developed on earth. In order to replicate, DNA requires protein enzymes like deoxyribonuclease (DNase). These enzymes can only be created by the complex machinery of DNA, RNA, and ribosomes. It is hard to image all these different kinds of molecules coming into existence at once.

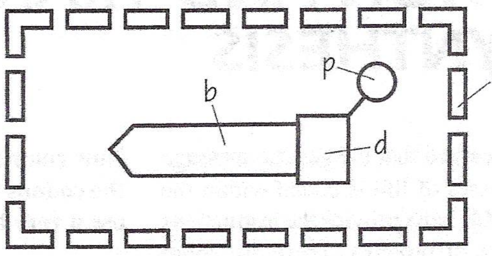
RNA, on the other hand, can take on a number of enzymatic functions as well as carrying the genetic message. Thus we can conceive of a simpler world in which a single self-replicating molecule spawned by the hot chemical soup of the early earth, like a single-person office, got the business of life off to a shaky beginning. Some viruses, which are the simplest known organisms, use RNA instead of DNA as their genetic material. The human immunodeficiency virus that causes AIDS is one of these.

The advantage of DNA over RNA is that it reproduces the genetic message much more accurately when it replicates. RNA is less stable and undergoes about a million times more mutations in the same period of time as DNA does. This can be an advantage in pathogens like HIV, because it permits the virus to keep changing and so escape its host's immune response. For large creatures like ourselves, though, that rate of mutation would almost certainly lead to rapid extinction. Sometime during the first billion or so years of earth history, DNA probably replaced RNA as the boss of the cellular office but kept RNA around to run vital messages.

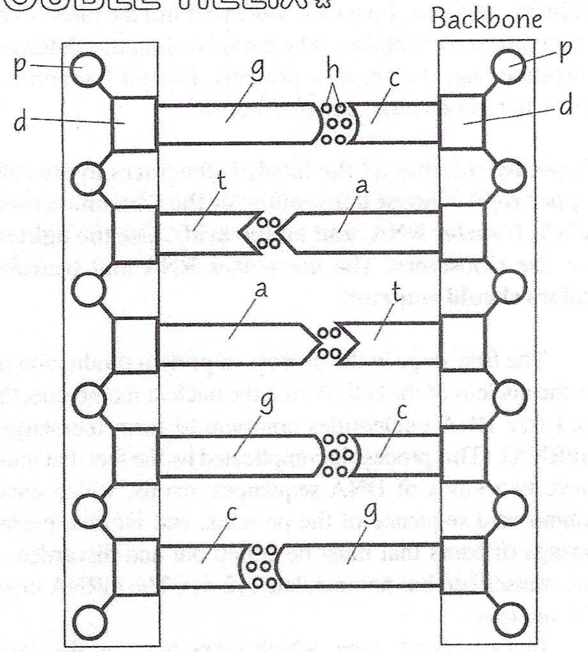
The next plate shows how messenger RNA (mRNA) relays information from the cell's nucleus to the cytoplasm—in particular to the ribosomes—where it provides the manufacturing plans for protein production.

DNA AND RNA MOLECULES

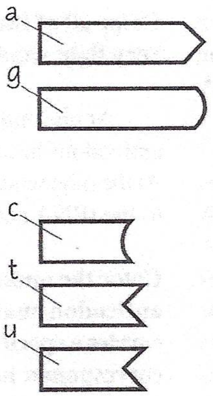
NUCLEOTIDE$_n$
PHOSPHATE$_p$
SUGAR*
DEOXYRIBOSE$_d$
RIBOSE$_r$
BASE$_b$



DNA DOUBLE HELIX*



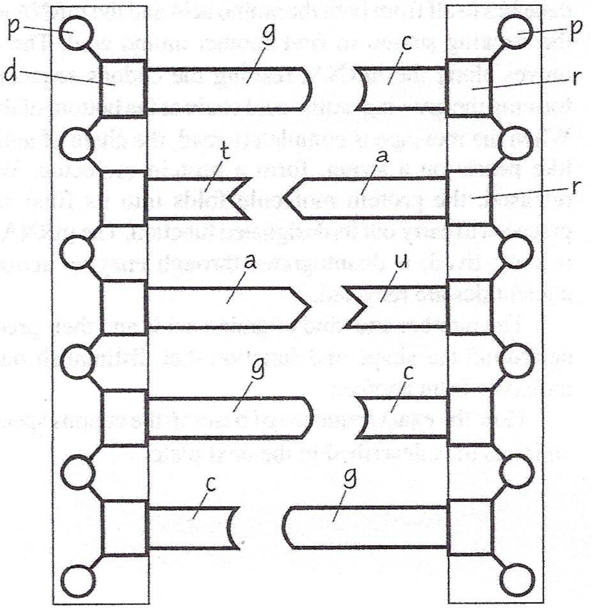
BASE*
PURINE*
ADENINE$_a$
GUANINE$_g$
PYRIMIDINE*
CYTOSINE$_c$
THYMINE$_t$
URACIL$_u$

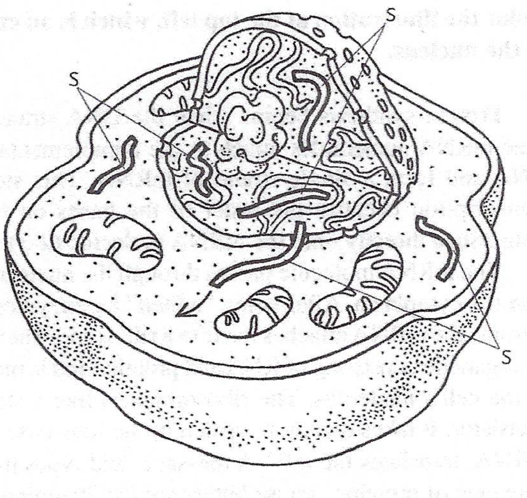


HYDROGEN BOND$_h$

TRANSCRIPTION OF DNA TO RNA*

DNA STRAND* RNA STRAND$_s$





2-4

TRANSCRIPTION AND TRANSLATION: PROTEIN SYNTHESIS

In the three previous plates we learned that the genetic message necessary to direct all the processes of life is coded within the DNA. Genes strung along the double helix provide the instructions for the synthesis or manufacture of proteins. There are about 100,000 proteins in the human body. Proteins (Greek for primary), are molecules that perform many functions in the body. They are the major components of skin, muscle, and organs like the heart, kidneys, and liver. Enzymes, which control the rates of chemical reactions, and antibodies, which provide immune defense against infectious agents, are also proteins. Protein hormones control growth, reproduction, and metabolism.

Begin by coloring all the labeled structures in the cell in the upper right. Choose light colors for the ribosomes, messenger RNA, transfer RNA, and amino acids. Use the lightest color for the ribosomes. The messenger RNA and transfer RNA colors should contrast.

The first stage in the process of protein production happens in the nucleus of the cell. Within the nuclear membrane, the DNA and free RNA nucleotides combine to form messenger RNA (mRNA). (This process is complicated by the fact that most genes have two kinds of DNA sequences: exons, which encode the amino acid sequence of the proteins, and introns, meaningless strings of bases that must be edited out and discarded. Introns are transcribed but not translated [2-6]). The mRNA then leaves the nucleus.

In the second stage, which takes place in the cytoplasm, special enzymes clip out the introns (not shown), and the shortened "edited" mRNA combines with ribosomes, transfer RNA (tRNA), and amino acids to construct the amino acid chains that form proteins.

Color the illustration at the top left, which is an enlargement of the nucleus.

Protein synthesis begins when the DNA strands separate. Free mRNA nucleotides attach to the complementary bases of DNA and form a single strand of mRNA. This step is called transcription because the order of the bases on the DNA is transcribed directly onto the mRNA molecule (2-3).

The mRNA molecule passes through the nuclear membrane into the cytoplasm. After being "edited" by enzymes to remove introns, the mRNA attaches itself to a ribosome. The ribosome is an organelle consisting of RNA and proteins and is manufactured in the cell's nucleolus. The ribosome acts like a stenographer/translator. It takes dictation written in the four-base alphabet of mRNA, translates the mRNA message, and types it up into the language of proteins, whose letters are the 20 amino acids.

Now color the enlarged ribosome and the mRNA, including the codons that run through the ribosome. It is important to use a very light shade of the mRNA color for the codons.

As the mRNA attaches to the ribosome, a "docking station" is formed where the mRNA bases are exposed three at a time, as the patterns indicate. This step of protein synthesis is called translation. Each set of three mRNA bases, called a codon, acts like a code word that translates into a particular amino acid in the developing "protein necklace."

Transfer RNA (tRNA) accomplishes this translation process by matching each codon to the appropriate amino acid.

Color all of the transfer RNA, each with its anticodon. Use a very light shade of the tRNA color for the anticodon.

At one end, each tRNA molecule has three base pairs called anticodons because they are complementary to an mRNA codon. At the other end of the tRNA, a specific amino acid corresponding to the tRNA anticodon becomes attached.

Color the amino acids and note that the pattern on the tRNA anticodon matches the attached amino acid. Each tRNA carries a specific amino acid. The pattern on the mRNA codon corresponds to the tRNA codon as well. Color the peptide bonds formed between linked amino acids.

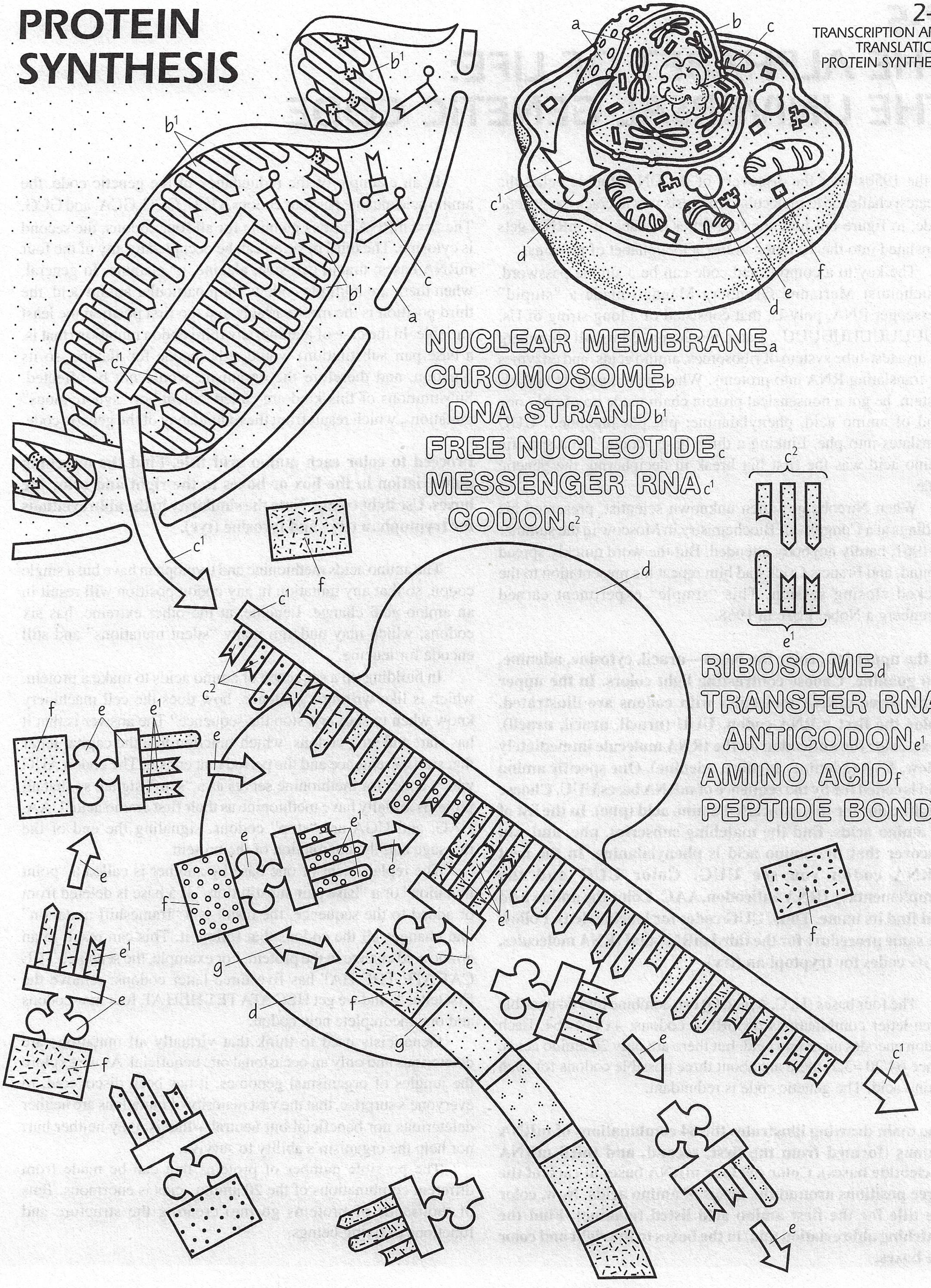
The job of the tRNA molecule is to transport its particular amino acid to the ribosome. There, the tRNA molecule attaches by hydrogen bonds to its complementary codon on the mRNA molecule.

When two tRNAs are attached to the mRNA, a peptide bond is formed between the adjacent amino acids. The tRNA then detaches itself from both the amino acid and the mRNA and leaves the docking station to find another amino acid. The ribosome moves along the mRNA, reading the codons sequentially and forming the growing amino acid chain at the bottom of the picture. When the message is completely read, the chain of amino acids, like pearls on a string, form a protein molecule. When it is released, the protein molecule folds into its final shape and proceeds to carry out its designated function. The mRNA molecule is short-lived: it disintegrates through enzyme action and its nucleotides are recycled.

The number and kind of amino acids and their precise order determine the shape and function that distinguish one protein molecule from another.

How the exact sequence of bases in the codons specifies each amino acid is described in the next plate.

PROTEIN SYNTHESIS



NUCLEAR MEMBRANE$_a$
CHROMOSOME$_b$
DNA STRAND$_{b^1}$
FREE NUCLEOTIDE$_c$
MESSENGER RNA$_{c^1}$
CODON$_{c^2}$

RIBOSOME$_d$
TRANSFER RNA$_e$
ANTICODON$_{e^1}$
AMINO ACID$_f$
PEPTIDE BOND$_g$