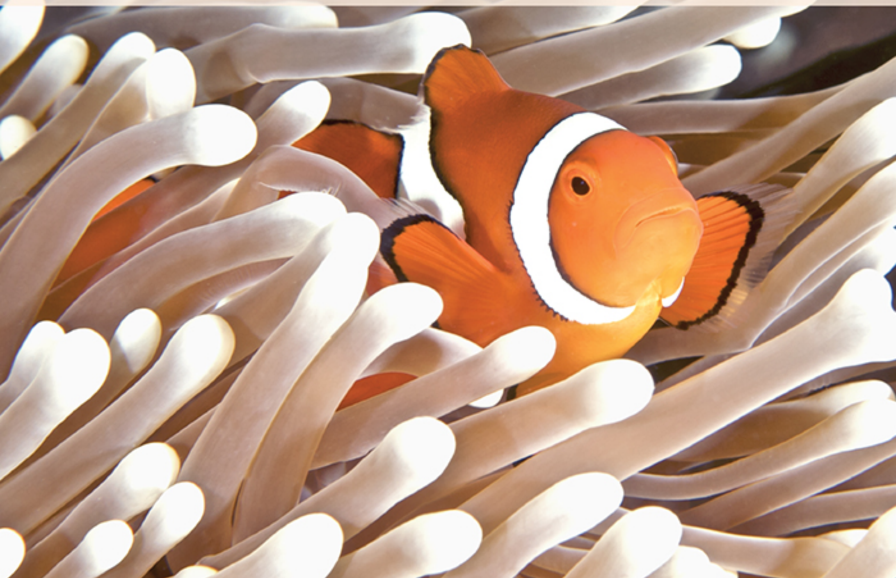
GLOBAL EDITION

BIOLOGY

SCIENCE FOR LIFE WITH PHYSIOLOGY

FIFTH EDITION

Colleen Belk • Virginia Borden Maier



ALWAYS LEARNING

PEARSON

Biology

Science for Life

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PEARSON

Pet fish have been genetically modified so that they glow.

9.1 Protein Synthesis and Gene Expression

To genetically modify foods, scientists can move a gene known to produce a certain protein from one organism to another. Alternatively, scientists can change the amount of protein a gene produces. Regulating the amount of protein produced by a cell is also referred to as *regulating gene expression*.

One of the first examples of scientists controlling gene expression occurred in the early 1980s when genetic engineers began to produce **recombinant bovine growth hormone (rBGH)** in their laboratories. Recombinant (r) bovine growth hormone is a protein that is made by genetically engineered bacteria. These bacterial cells have had their DNA manipulated so that it carries the instructions for, or encodes, a cow growth hormone that can be produced in the laboratory. Growth hormones act on many different organs to increase the overall size of the body. Bovine growth hormone that is produced in a laboratory can be injected into dairy cows to increase their milk production.

Production of growth hormone protein, or any protein, in the lab or in a cell, requires the use of the genetic information coded in the DNA.

From Gene to Protein

Protein synthesis involves using the instructions carried by a gene to build a particular protein. Genes do not build proteins directly; instead, they carry the instructions that dictate how a protein should be built. Understanding protein synthesis requires that we review a few basics about DNA, genes, and RNA. First, DNA is a polymer of **nucleotides** that make chemical bonds with each other based on their complementarity: adenine (A) to thymine (T) and cytosine (C) to guanine (G). Second, a gene is a sequence of DNA that encodes a protein.

nucleo- or **nucl-** refers to a nucleus.

Proteins are large molecules composed of amino acids. Each protein has a unique function that is dictated by its particular structure. The structure of a protein is the result of the order of amino acids that constitute it because the chemical properties of amino acids cause a protein to fold in a particular manner. Before a protein can be built, the instructions carried by a gene are first copied. When the gene is copied, the copy is made up not of DNA (deoxyribonucleic acid) but of **RNA (ribonucleic acid).**

-ic is a common ending of acids.

RNA, like DNA, is a polymer of nucleotides. A nucleotide is composed of a sugar, a phosphate group, and a nitrogen-containing base. Whereas the sugar in DNA is deoxyribose, the sugar in RNA is **ribose.** RNA has the nitrogenous base uracil (U) in place of thymine. RNA is usually single stranded, not double stranded like DNA (**FIGURE 9.1**).

-ose is a common ending for sugars.

When a cell requires a particular protein, a strand of RNA is produced using DNA as a guide or template. RNA nucleotides are able to make base pairs with DNA nucleotides. C pairs with G, and A pairs with U. The RNA copy then serves as a blueprint that tells the cell which amino acids to join together to produce a protein. Thus, the flow of genetic information in a eukaryotic cell is from DNA to RNA to protein (**FIGURE 9.2**).

How does this flow of information actually take place in a cell? Going from gene to protein involves two steps. The first step, called **transcription,** involves producing the copy of the required gene. In the same way that a transcript of a speech is a written version of the oral presentation, transcription inside a cell produces a transcript of the original gene, with the RNA nucleotides substituted for DNA nucleotides. The second step, called **translation,** involves decoding the copied RNA sequence and producing the protein for which it codes. In the same way that a translator deciphers one language into another, translation in a cell involves moving from the language of nucleotides (DNA and RNA) to the language of amino acids and proteins.

Visualize This

Point out the chemical difference between the sugar in DNA and the one in RNA and the difference between the nitrogenous bases thymine and uracil.

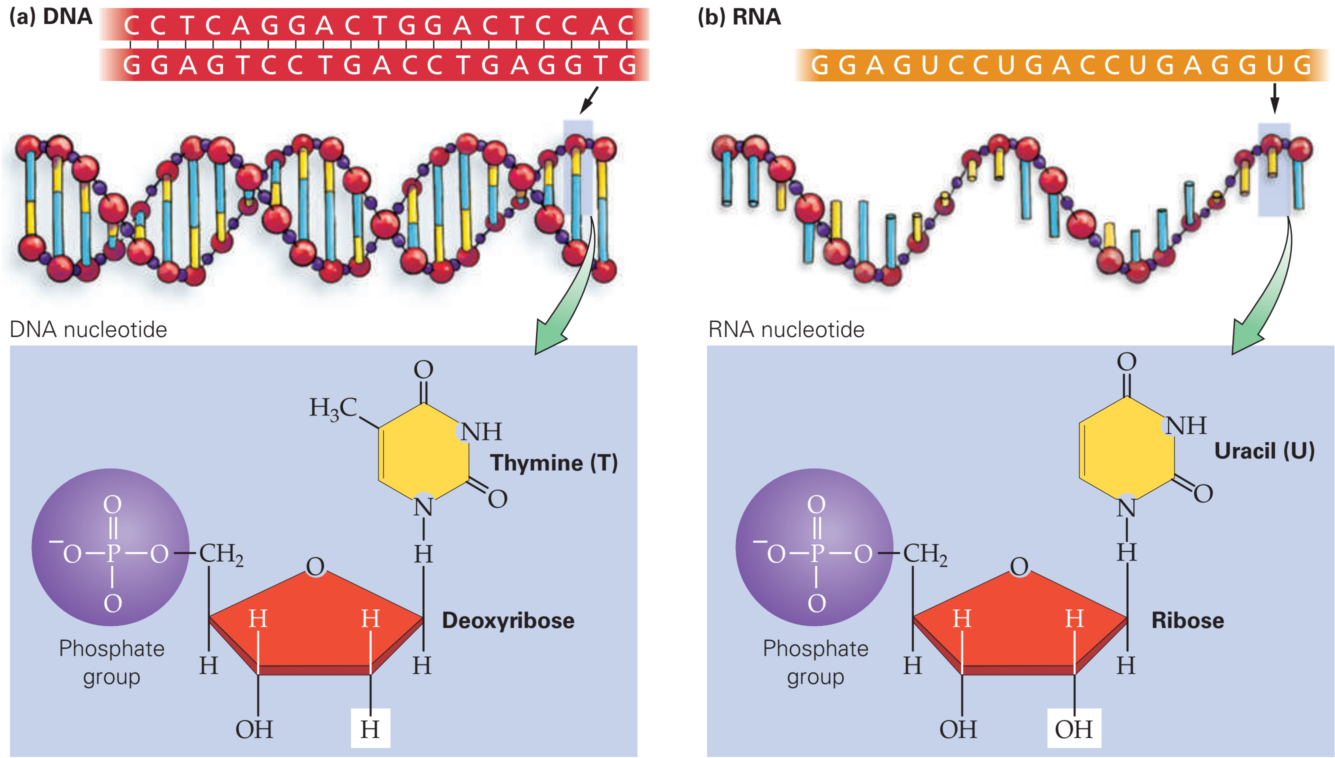

FIGURE 9.1 DNA and RNA. (a) DNA is double stranded. Each DNA nucleotide is composed of the sugar deoxyribose, a phosphate group, and a nitrogen-containing base (A, G, C, or T). (b) RNA is single stranded. RNA nucleotides are composed of the sugar ribose, a phosphate group, and a nitrogen-containing base (A, G, C, or U).

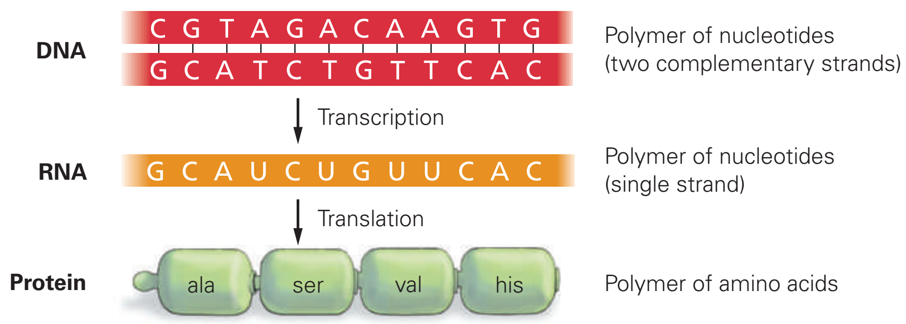

FIGURE 9.2 The flow of genetic information. Genetic information flows from DNA to an RNA copy of the DNA gene, to the amino acids that are joined together to produce the protein coded for by the gene.

Visualize This

Divide the number of nucleotides by the number of amino acids to determine how many nucleotides are required to encode each amino acid.

Transcription

Transcription is the copying of a DNA gene into RNA. The copy is synthesized by an enzyme called **RNA polymerase.** To begin transcription, the RNA polymerase binds to a nucleotide sequence at the beginning of every gene, called the **promoter.** Once the RNA polymerase has located the beginning of the gene by binding to the promoter, it then rides along the strand of the DNA helix that comprises the gene (**FIGURE 9.3**). As it is traveling along the gene, the RNA polymerase unzips the DNA double helix and ties together RNA nucleotides that are complementary to the DNA strand it is using as a template. This results in the production of a single-stranded RNA molecule that is complementary to the DNA sequence of the gene. This complementary RNA copy of the DNA gene is called **messenger RNA (mRNA)** because it carries the message of the gene that is to be expressed.

Visualize This

Propose a sequence for the DNA strand that is being used to produce the mRNA. Keep in mind that purines (A and G) are composed of two rings and thus are represented by longer pegs in this illustration. Once you have proposed a DNA sequence, determine the mRNA sequence that would be produced by transcription.

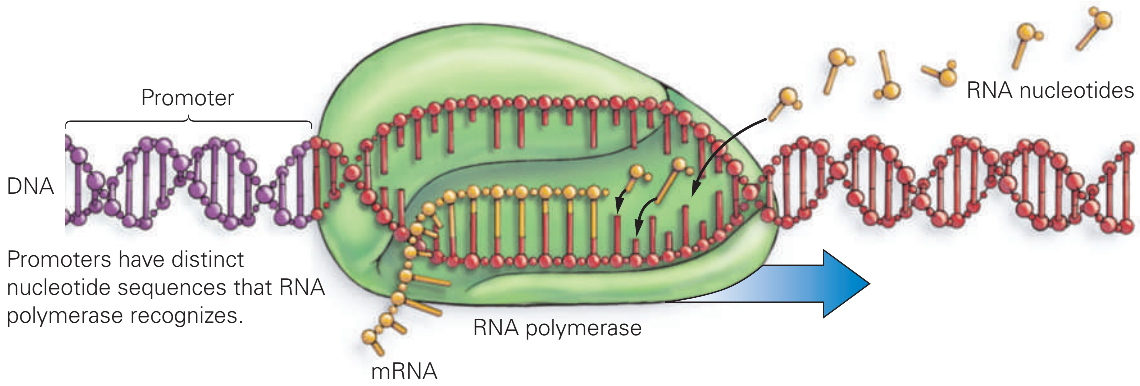

FIGURE 9.3 Transcription. RNA polymerase ties together nucleotides within the growing RNA strand as they form hydrogen bonds with their complementary base on the DNA. When the RNA polymerase reaches the end of the gene, the mRNA transcript is released.

Translation

The second step in moving from gene to protein, translation, requires that the mRNA be used to produce the actual protein for which the gene encodes. For this process to occur, a cell needs mRNA, a supply of amino acids to join in the proper order, and some energy in the form of ATP. Translation also requires structures called ribosomes and transfer RNA molecules.

-some and **somal** relate to a body.

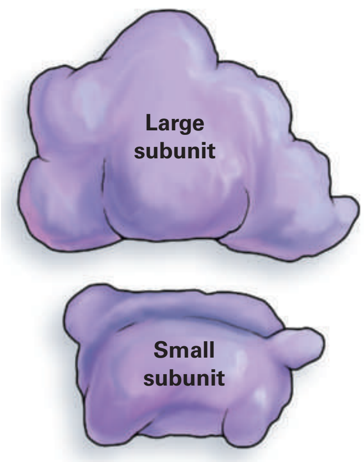

FIGURE 9.4 Ribosome. Ribosomes are composed of two subunits. Each subunit in turn is composed of rRNA and protein.

Ribosomes. **Ribosomes** are subcellular, globular structures (**FIGURE 9.4**) that are composed of another kind of RNA called **ribosomal RNA (rRNA),** which is wrapped around many different proteins. Each ribosome is composed of two subunits—one large and one small. When the large and small subunits of the ribosome come together, the mRNA can be threaded between them. In addition, the ribosome can bind to structures called **transfer RNA (tRNA)** that carry amino acids.

Transfer RNA (tRNA). Transfer RNA (**FIGURE 9.5**) is yet another type of RNA found in cells. An individual transfer RNA molecule carries one specific amino acid and interacts with mRNA to place the amino acid in the correct location of the growing polypeptide.

As mRNA moves through the ribosome, small sequences of nucleotides are sequentially exposed. These sequences of mRNA, called **codons,** are three nucleotides long and encode a particular amino acid. Transfer RNAs also have a set of three nucleotides, which will bind to the codon if the right sequence is present. These three nucleotides at the base of the tRNA are called the **anticodon** because they complement a codon on mRNA. The anticodon on a particular tRNA binds to the complementary mRNA codon. In this way, the codon calls for the incorporation of a specific amino acid. The ribosome moves along the mRNA sequentially exposing codons for tRNA binding.

When a tRNA anticodon binds to the mRNA codon, a peptide bond is formed. The ribosome adds the amino acid that the tRNA is carrying to the growing chain of amino acids that will eventually constitute the finished protein. The transfer RNA functions as a sort of cellular translator, fluent in both the language of nucleotides (its own language) and the language of amino acids (the target language).

To help you understand protein synthesis, let us consider its similarity to an everyday activity such as baking a cake (**FIGURE 9.6**). To bake a cake, you would consult a recipe book (genome) for the specific recipe (gene) to make your cake (protein). You may copy the recipe (mRNA) out of the book so that the original recipe (gene) does not become stained or damaged. The original recipe (gene) is left in the book (genome) on a shelf (nucleus) so that you can make another copy when you need it. The original recipe (gene) can be copied again and again. The copy of the recipe (mRNA) is placed on the kitchen counter (ribosome) while you assemble the ingredients (amino acids). The ingredients (amino acids) for your cake (protein) include flour, sugar, butter, milk, and eggs. The ingredients are measured in measuring spoons and cups (tRNAs). (While in baking you might use the same cups and spoons for several ingredients, in protein synthesis we use tRNAs that are dedicated to one specific ingredient.) The measuring spoons and cups bring the ingredients to the kitchen counter. Like the ingredients in a cake that can be used in many ways to produce a variety of foods, amino acids can be combined in different orders to produce different proteins. The ingredients (amino acids) are always added according to the instructions specified by the original recipe (gene). Within cells, the sequence of bases in the DNA dictates the sequence of bases

Visualize This

The structure of a tRNA molecule involves regions where the RNA strand forms complementary bonds with itself, causing the RNA to fold up on itself. What nitrogenous bases might be involved in bonding in such regions of internal complementarity?

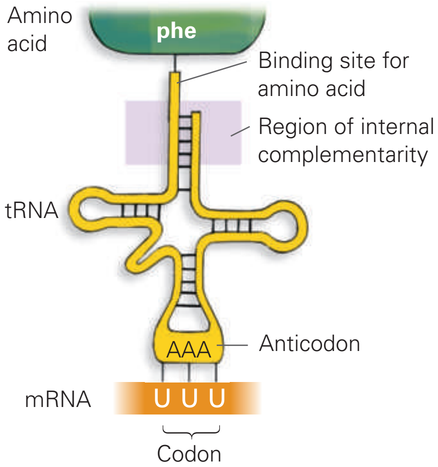

FIGURE 9.5 Transfer RNA (tRNA). Transfer RNAs translate the language of nucleotides into the language of amino acids. The tRNA that binds to UUU carries only one amino acid (phe, the three-letter abbreviation for phenylalanine).

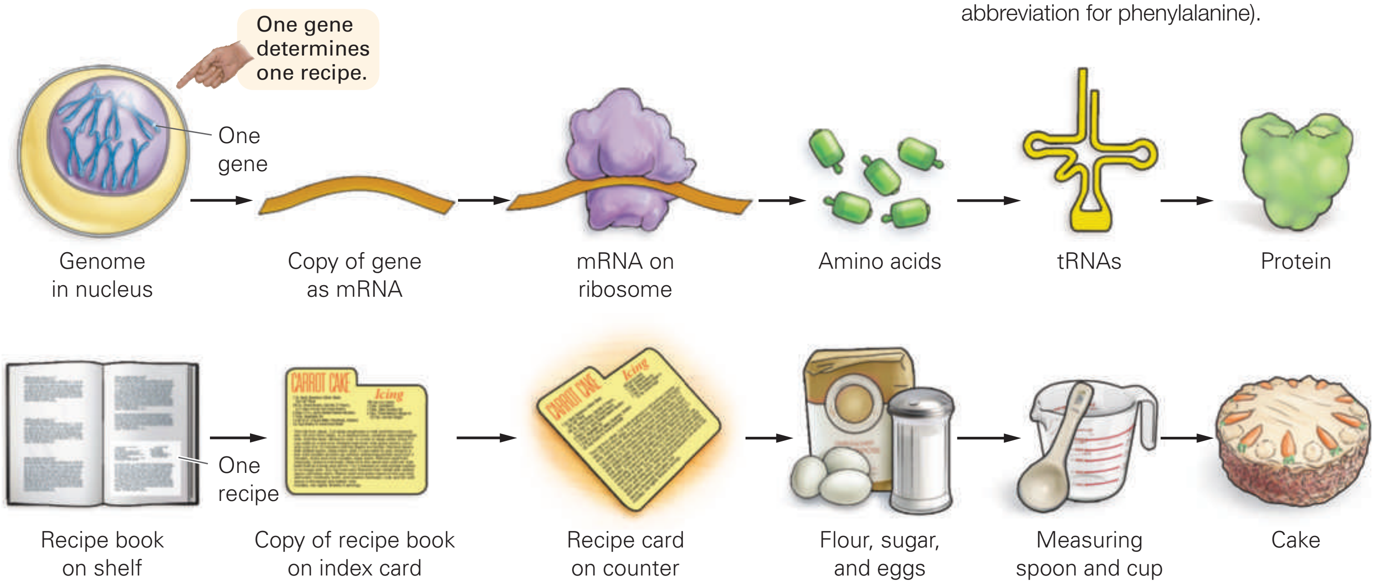

FIGURE 9.6 Protein synthesis and cake baking. A recipe book on a shelf resembles the genome in the nucleus of a cell. Copying one recipe onto an index card is similar to copying the gene to produce mRNA. The recipe card is placed on the kitchen counter, and the mRNA is placed on the ribosome. The ingredients for a cake are flour, sugar, butter, milk, and eggs. The ingredients to make a protein are various amino acids. The ingredients are measured in measuring spoons and cups (tRNAs) that are dedicated to one specific ingredient. The measuring spoons and cups bring the ingredients to the kitchen counter. The ingredients (amino acids) are always added according to the instructions specified by the original recipe (gene).

in the RNA, which in turn dictates the order of amino acids that will be joined together to produce a protein. Protein synthesis ends when a codon that does not code for an amino acid, called a **stop codon,** moves through the ribosome. When a stop codon is present in the ribosome, no new amino acid can be added, and the growing protein is released. Once released, the protein folds up on itself and moves to where it is required in the cell. A summary of the process of translation is shown in **FIGURE 9.7**.

The process of translation allows cells to join amino acids in the sequence coded by the gene. Scientists can determine the sequence of amino acids that a gene calls for by looking at the **genetic code.**

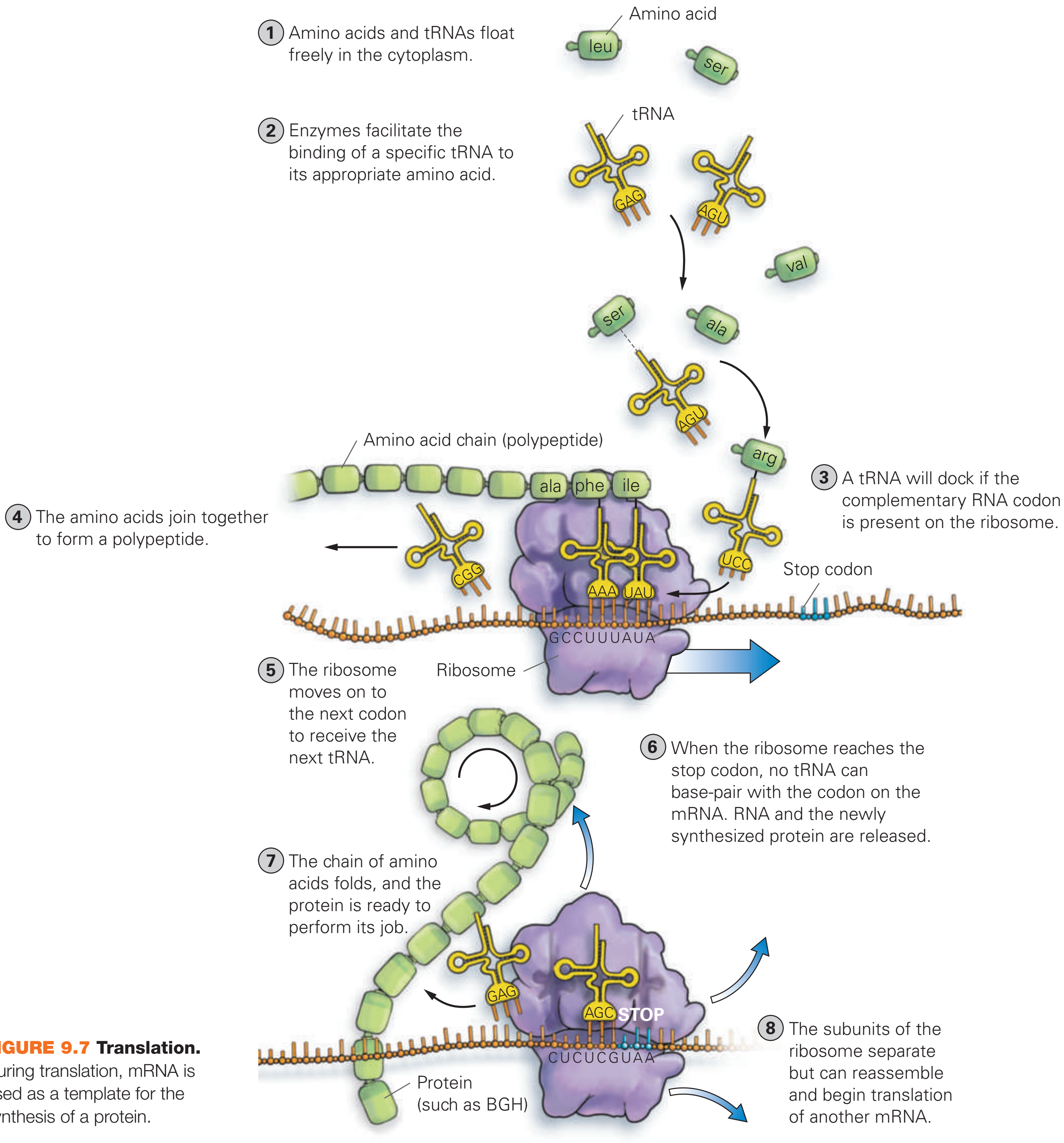

FIGURE 9.7 Translation. During translation, mRNA is used as a template for the synthesis of a protein.

Genetic Code. The genetic code shows which mRNA codons code for which amino acids. As **TABLE 9.1** shows, there are 64 codons, 61 of which code for amino acids. Three of the codons are stop codons that occur near the end of an mRNA. Because stop codons do not code for an amino acid, protein synthesis ends when a stop codon enters the ribosome. In the table, you can see that the codon AUG functions both as a start codon (and thus is found near the beginning of each mRNA) and as a codon dictating that the amino acid methionine (met) be incorporated into the protein being synthesized. This initial methionine is often removed later.

The genetic code has some additional properties to take note of. The code is redundant without being ambiguous, and it is also universal. The redundancy of the code can be seen in examples where the same amino acid is coded for by more than one codon. For example, the amino acid threonine (thr) is incorporated into a protein in response to the codons ACU, ACC, ACA, and ACG. There is, however, no situation where a given codon can call for more than one amino acid. For example, AGU codes for serine (ser) and nothing else. Therefore, there is no ambiguity in the genetic code regarding which amino acid any codon will call for. The genetic code is also universal in the sense that organisms typically decode the same gene to produce the same protein. This is why genes can be moved from one organism to another.

STOP & STRETCH What amino acids would be coded for by the mRNA CCU-AAU? Are there other codons that code for these amino acids?

TABLE 9.1 The genetic code.

To determine which amino acid is coded for by each mRNA codon, first look at the left-hand side of the chart for the first-base nucleotide in the codon; there are four rows, one for each possible RNA nucleotide—A, C, G, or U. Then look at the intersection of the second-base columns at the top of the chart and the first-base rows to narrow your search. Finally, the third-base nucleotide in the codon on the right-hand side of the chart determines the amino acid that a given mRNA codon codes for. Note the three codons UAA, UAG, and UGA that do not code for an amino acid; these are stop codons. The codon AUG is a start codon, found at the beginning of most protein-coding sequences.

First base	Second base: U		Second base: C		Second base: A		Second base: G		Third base
U	UUU	Phenylalanine (phe)	UCU	Serine (ser)	UAU	Tyrosine (tyr)	UGU	Cysteine (cys)	U
	UUC		UCC		UAC		UGC		C
	UUA	Leucine (leu)	UCA		UAA	**Stop codon**	UGA	**Stop codon**	A
	UUG		UCG		UAG	**Stop codon**	UGG	Tryptophan (trp)	G
C	CUU	Leucine (leu)	CCU	Proline (pro)	CAU	Histidine (his)	CGU	Arginine (arg)	U
	CUC		CCC		CAC		CGC		C
	CUA		CCA		CAA	Glutamine (gln)	CGA		A
	CUG		CCG		CAG		CGG		G
A	AUU	Isoleucine (ile)	ACU	Threonine (thr)	AAU	Asparagine (asn)	AGU	Serine (ser)	U
	AUC		ACC		AAC		AGC		C
	AUA		ACA		AAA	Lysine (lys)	AGA	Arginine (arg)	A
	AUG	Methionine (met) **Start codon**	ACG		AAG		AGG		G
G	GUU	Valine (val)	GCU	Alanine (ala)	GAU	Aspartic acid (asp)	GGU	Glycine (gly)	U
	GUC		GCC		GAC		GGC		C
	GUA		GCA		GAA	Glutamic acid (glu)	GGA		A
	GUG		GCG		GAG		GGG		G