

CHEM 3331  
Fundamentals of Biochemistry

Chapter

9

# Proteins

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*Organic and Biochemistry for Today*  
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## *Proteins*

- **Proteins** (Greek *proteios*, “primary” or “of first importance”) are biochemical molecules consisting of *polypeptides* joined by *peptide bonds* between the amino and carboxyl groups of *amino acid* residues.
- Proteins perform a number of vital functions:
  - *Enzymes* are proteins that act as biochemical catalysts.
  - Many proteins have structural or mechanical functions (e.g., actin and myosin in muscles).
  - Proteins are important in cell signaling, immune responses, cell adhesion, and the cell cycle.
  - Proteins are a necessary component in animal diets.

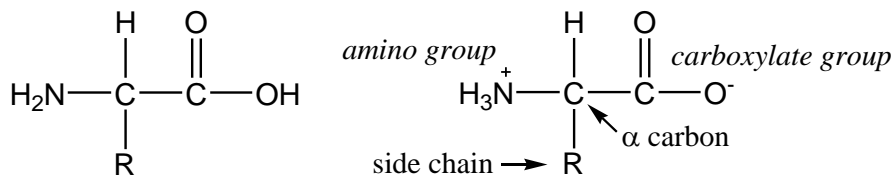
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# Amino Acids

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## Amino Acids

- All proteins are polymers containing chains of **amino acids** chemically bound by **amide (peptide) bonds**.
- Most organisms use 20 naturally-occurring amino acids to build proteins. The linear sequence of the amino acids in a protein is dictated by the sequence of the nucleotides in an organisms' genetic code.
- These amino acids are called **alpha ( $\alpha$ )-amino acids** because the amino group is attached to the first carbon in the chain connected to the carboxyl carbon.



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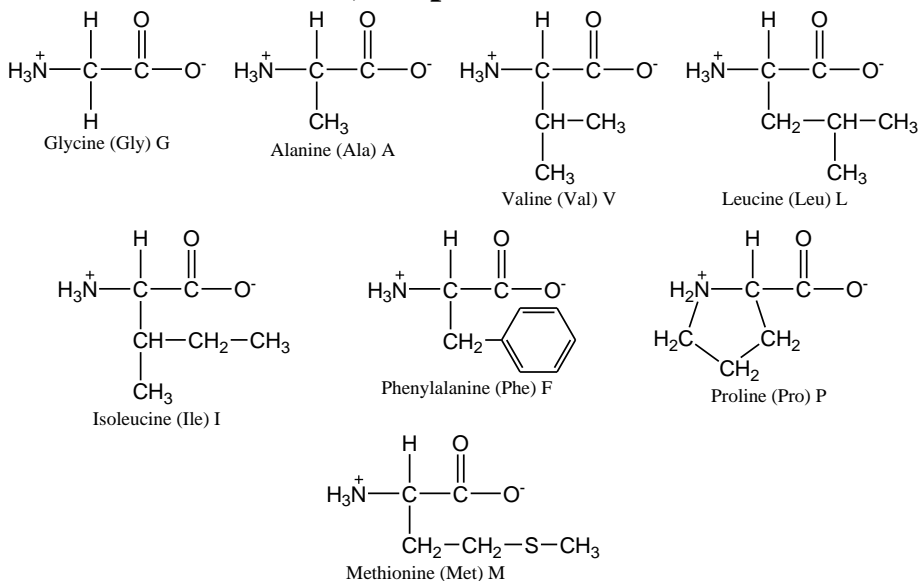
## *Amino Acids*

- The amino acids are classified by the polarity of the R group side chains, and whether they are acidic or basic:
  - neutral, nonpolar
  - neutral, polar
  - basic, polar (contains an additional amino group)
  - acidic, polar (contains an additional carboxylate group)
- All of the amino acids are also known by a three-letter and one-letter abbreviations.

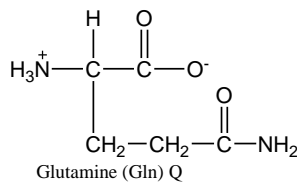
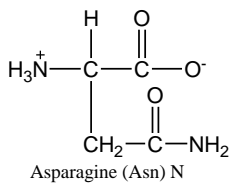
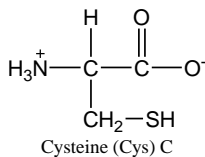
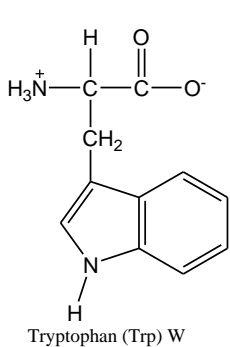
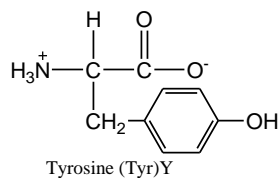
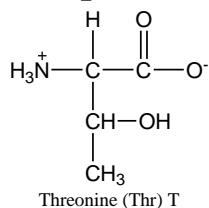
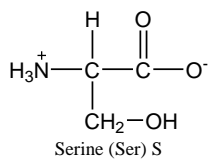
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### *Table 9.1: The Common Amino Acids*

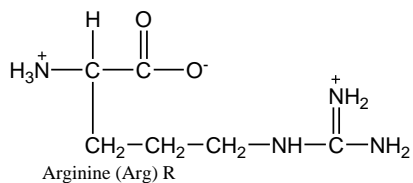
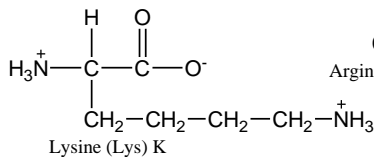
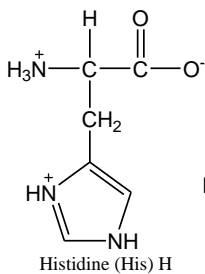
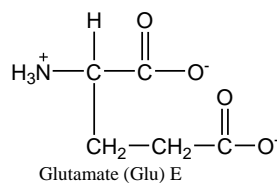
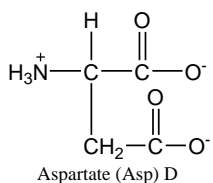
#### Neutral, nonpolar side chains



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*Table 9.1: The Common Amino Acids***Neutral, polar side chains**

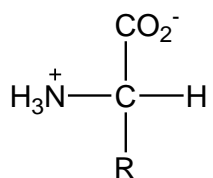
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*Table 9.1: The Common Amino Acids***Basic, polar side chains****Acidic, polar side chains**

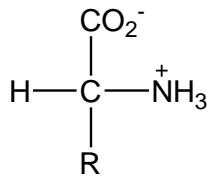
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## *Stereochemistry of the Amino Acids*

- Since the amino acids (except for glycine) contain four different groups connected to the  $\alpha$ -carbon, they are chiral, and exist in two enantiomeric forms:



an L-amino acid



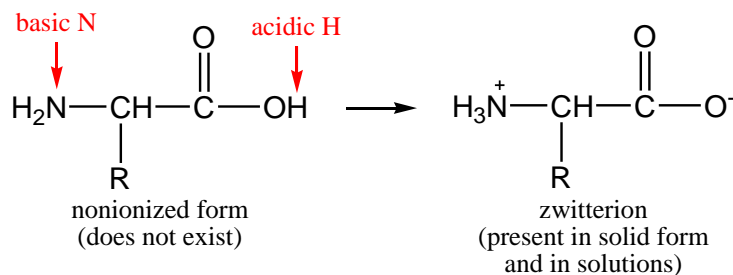
an R-amino acid

- The amino acids in living systems exist primarily in the L form.

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## *Zwitterions*

- Because amino acids contain both an acidic and a basic functional group, an internal acid-base reaction occurs, forming an ion with both a positive and a negative charge called a **zwitterion**:

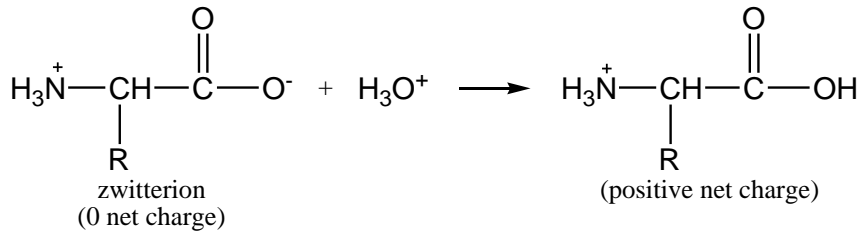


- In solution, the structure of an amino acid can change with the pH of the solution:

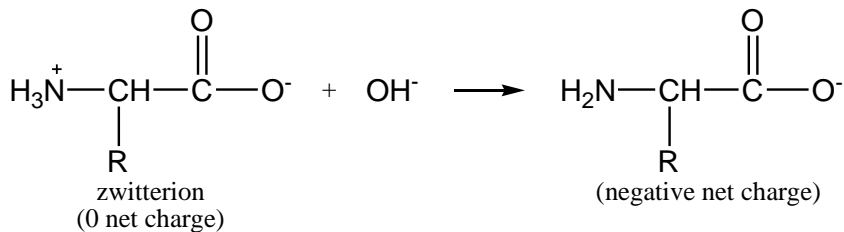
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## *Zwitterions*

- Lowering the pH of the solution causes the zwitterion to pick up a proton:



- Increasing the pH of the solution causes the zwitterion to lose a proton:



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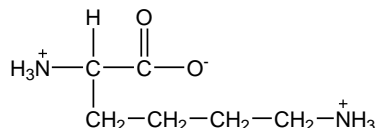
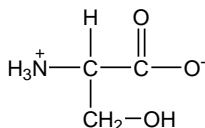
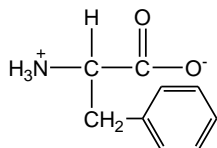
## *Zwitterions*

- Since the pH of the solution affects the charge on the amino acid, at some pH, the amino acid will form a zwitterion. This is called the **isoelectric point**.
- Each amino acid (and protein) has a characteristic isoelectric point: those with neutral R groups are near a pH of 6, those with basic R groups have higher values, and those with acidic R groups have lower values.
- Because amino acids can react with both  $\text{H}_3\text{O}^+$  and  $\text{OH}^-$ , solutions of amino acids and proteins can act as buffers. (E.g., blood proteins help to regulate the pH of blood.)

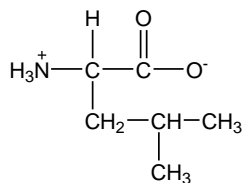
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### Examples: Amino Acid Structures

- Identify the following amino acid R groups as being polar or nonpolar, and acidic or basic:



- Draw the structure of the amino acid leucine (a) in acidic solution at a pH below the isoelectric point, and (b) in basic solution at a pH above the isoelectric point.



Leucine (Leu) L

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### Examples: Amino Acid Structures

- Draw Fischer projections representing the D and L form of aspartate and cysteine.

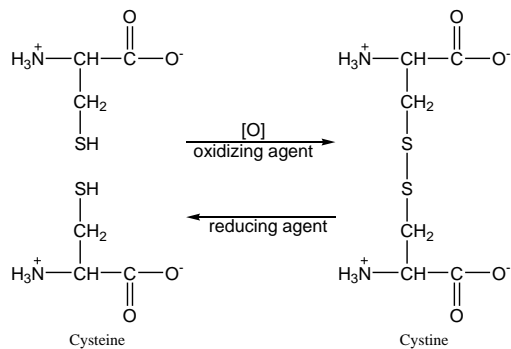
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# Reactions of Amino Acids

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## Oxidation of Cysteine

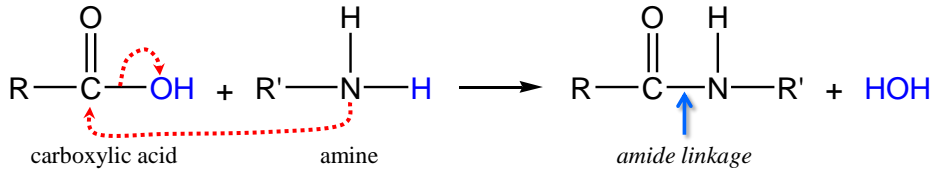
- Amino acids can undergo any of the reactions characteristic of the functional groups in the structure.
- Cysteine is the only amino acid that contains a sulfhydryl (thiol, R—SH) group. Thiols are easily oxidized to form disulfide bonds (R—S—S—R). This allows cysteine to dimerize to form *cystine*:



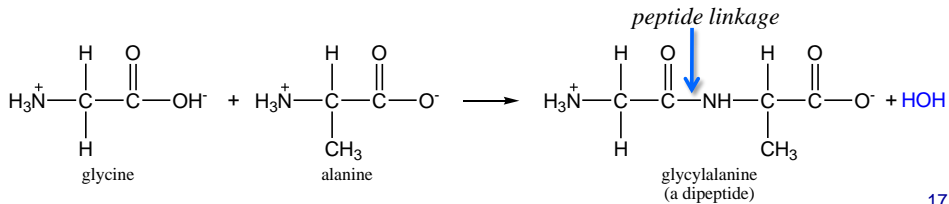
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## Peptide Formation

- Amides can be thought of as forming from the reaction of an amine and a carboxylic acid:



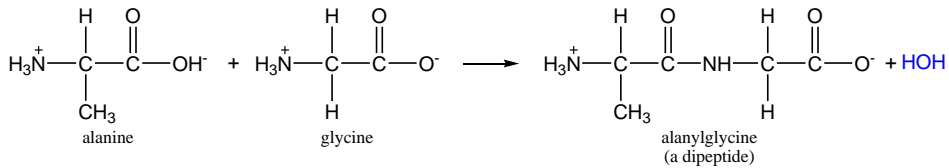
- In the same way, two amino acids can combine to form a **dipeptide**, held together by a **peptide bond**:



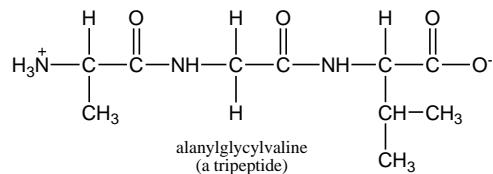
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## Peptide Formation

- The two amino acids can connect the other way as well, forming a structural isomer of the dipeptide, with a unique set of physical properties:



- A third amino acid can join the chain to form a tripeptide:



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## *Peptides*

- A fourth amino acid would form a tetrapeptide, a fifth would form a pentapeptide, and so on.
- Short chains are referred to as **peptides**, chains of up to about 50 amino acids are **polypeptides**, and chains of more than 50 amino acids are **proteins**. (The terms *protein* and *polypeptide* are often used interchangeably.)
- Amino acids in peptide chains are called **amino acid residues**.
  - The residue with a free amino group is called the **N-terminal residue**, and is written on the left end of the chain.
  - The residue with a free carboxylate group is called the **C-terminal residue**, and is written on the right end of the chain.

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## *Peptides*

- Peptides are named by starting at the N-terminal end and listing the amino acid residues from left to right.
- Large amino acid chains are unwieldy to draw in their complete forms, so they are usually represented by their three-letter abbreviations, separated by dashes:
  - Gly-Ala (Gly = N-terminal, Ala = C-terminal)
  - Ala-Gly (Ala = N-terminal, Gly = C-terminal)
- The tripeptide alanyl-glycylvaline can be written as Ala-Gly-Val. (There are five other arrangements of these amino acids that are possible.)
- Insulin has 51 amino acids, with  $1.55 \times 10^{66}$  different possible arrangements, but the body produces only one.

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### *Examples: Reactions of Amino Acids*

- Write two reactions to represent the formation of the two dipeptides that form when valine and serine react.
  
- Write a complete structural formula and an abbreviated formula for the tripeptide formed from aspartate, cysteine, and valine in which the C-terminal residue is cysteine and the N-terminal residue is valine.

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### *Examples: Reactions of Amino Acids*

- How many tripeptide isomers that contain one residue each of valine, phenylalanine, and lysine are possible? Write the abbreviated formulas for these peptides.

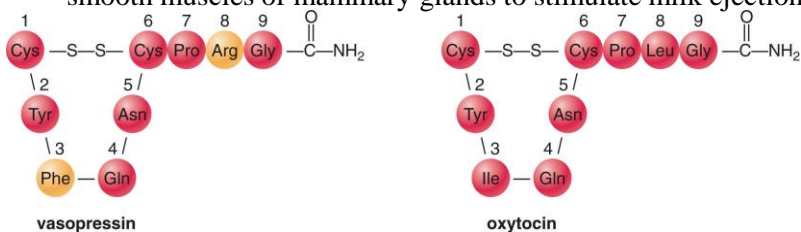
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# Important Peptides

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## *Vasopressin and Oxytocin*

- More than 200 peptides have been identified as being essential to the body's proper functioning.
- Vasopressin and oxytocin are nonapeptide hormones secreted by the pituitary gland. Six of the amino acid residues are held in a loop by **disulfide bridges** formed by the oxidation of two cysteine residues. Even though the molecules are very similar, their biological functions are quite different:
  - Vasopressin is known as antidiuretic hormone (ADH) because it reduces the amount of urine formed, which causes the body to conserve water. It also raises blood pressure.
  - Oxytocin causes the smooth muscles of the uterus to contract, and is administered to induce labor. It also stimulates the smooth muscles of mammary glands to stimulate milk ejection.



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## *Adrenocorticotrophic hormone*

- Adrenocorticotrophic hormone (ACTH) is a 39-residue peptide produced in the pituitary gland. It regulates the production of steroid hormones in the cortex of the adrenal gland.



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## *Examples of Peptide and Protein Hormones*

Name	Origin	Action
Adrenocorticotrophic hormone (ACTH)	Pituitary	Stimulates production of adrenal hormones
Angiotensin II	Blood plasma	Causes blood vessels to constrict
Follicle-stimulating hormone (FSH)	Pituitary	Stimulates sperm production and follicle maturation
Gastrin	Stomach	Stimulates stomach to secrete acid
Glucagon	Pancreas	Stimulates glycogen metabolism in liver
Human growth hormone (HGH)	Pituitary	General effects; bone growth
Insulin	Pancreas	Controls metabolism of carbohydrates
Oxytocin	Pituitary	Stimulates contraction of the uterus and other smooth muscles
Prolactin	Pituitary	Stimulates lactation
Somatostatin	Hypothalamus	Inhibits production of HGH
Vasopressin	Pituitary	Decreases volume of urine excreted

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# Characteristics of Proteins

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## *Size of Proteins*

- Proteins are very large polymers of amino acids with molecular weights that vary from 6000 amu to several million amu.
  - Glucose ( $C_6H_{12}O_6$ ) = 180 amu
  - Hemoglobin ( $C_{2952}H_{4664}O_{832}N_{812}S_8Fe_4$ ) = 65,000 amu

Protein	Molecular Weight (amu)	Number of Amino Acid Residues
Insulin	6,000	51
Cytochrome c	16,000	104
Growth hormone	49,000	191
Rhodopsin	38,900	348
Hemoglobin	65,000	574
Hexokinase	96,000	730
Gamma globulin	176,000	1320
Myosin	800,000	6100

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## *Size of Proteins*

- Proteins are too large to pass through cell membranes, and are contained within the cells where they were formed unless the cell is damaged by disease or trauma.
  - Persistent large amounts of protein in the urine are indicative of damaged kidney cells.
  - Heart attacks can also be confirmed by the presence of certain proteins in the blood that are normally confined to cells in heart tissue.

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## *Acid-Base Properties*

- Proteins take the form of zwitterions. They have characteristic isoelectric points, and can behave as buffers in solutions.
- The tendency for large molecules to remain in solution or form stable colloidal dispersions depends on the repulsive forces acting between molecules with like charges on their surfaces.
  - When proteins are at a pH in which there is a net positive or negative charge, the like charges cause the molecules to repel one another, and they remain dispersed.
  - When the pH is near the isoelectric point, the net charge on the molecule is zero, and the repulsion between proteins is small. This causes the protein molecules to clump and precipitate from solution.

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## *Protein Function*

- Proteins perform crucial roles in all biological processes.
- 1. Catalytic function:** Nearly all reactions in living organisms are catalyzed by proteins functioning as *enzymes*. Without these catalysts, biological reactions would proceed much more slowly.
  - 2. Structural function:** In animals structural materials other than inorganic components of the skeleton are proteins, such as *collagen* (mechanical strength of skin and bone) and *keratin* (hair, skin, fingernails).
  - 3. Storage function:** Some proteins provide a way to store small molecules or ions, e.g., ovalbumin (used by embryos developing in bird eggs), casein (a milk protein) and gliadin (wheat seeds), and ferritin (a liver protein which complexes with iron ions).

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## *Protein Function*

- 4. Protective function:** **Antibodies** are proteins that protect the body from disease by combining with and destroying viruses, bacteria, and other foreign substances. Another protective function is *blood clotting*, carried out by thrombin and fibrinogen.
- 5. Regulatory function:** Body processes regulated by proteins include growth (growth hormone) and thyroid functions (thyrotropin).
- 6. Nerve impulse transmission:** Some proteins act as receptors for small molecules that transmit impulses across the synapses that separate nerve cells. (Rhodopsin in vision, xxxxx)
- 7. Movement function:** The proteins actin and myosin are important in muscle activity, regulating the contraction of muscle fibers.

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## *Protein Function*

- 8. Transport function:** Some proteins bind small molecules or ions and transport them through the body.
- Serum albumin is a blood protein that carries fatty acids between fat (adipose) tissue and other organs.
  - Hemoglobin carries oxygen from the lungs to other body tissues.
  - Transferrin is a carrier of iron in blood plasma.
- A typical human cell contains 9000 different proteins; the human body contains about 100,000 different proteins.

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*Table 19.4 Biological Functions of Proteins*

Function	Examples	Occurrence or role
Catalysis	lactate dehydrogenase	Oxidizes lactic acid
	cytochrome c	Transfers electrons
	DNA polymerase	Replicates and repairs DNA
Structure	viral-coat proteins	Sheath around nucleic acid of virus
	glycoproteins	Cell coats and walls
	$\alpha$ -keratin	Skin, hair, feathers, nails, and hooves
	$\beta$ -keratin	Silk of cocoons and spiderwebs
	collagen	Fibrous connective tissue
	elastin	Elastic connective tissue
Storage	ovalbumin	Egg-white protein
	casein	A milk protein
	ferritin	Stores iron in the spleen
	gliadin	Stores amino acids in wheat
	zein	Stores amino acids in corn

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*Table 19.4 Biological Functions of Proteins*

Function	Examples	Occurrence or role
Protection	antibodies	Form complexes with foreign proteins
	fibrinogen	Involved in blood clotting
	thrombin	Involved in blood clotting
Regulation	insulin	Regulates glucose metabolism
	growth hormone	Stimulates growth of bone
Nerve impulse transmission	rhodopsin	Involved in vision
	acetylcholine receptor protein	Impulse transmission in nerve cells
Movement	myosin	Thick filaments in muscle fiber
	actin	Thin filaments in muscle fiber
	dynein	Movement of cilia and flagella
Transport	hemoglobin	Transports O <sub>2</sub> in blood
	myoglobin	Transports O <sub>2</sub> in muscle cells
	serum albumin	Transports fatty acids in blood
	transferrin	Transports iron in blood
	ceruloplasmin	Transports copper in blood

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### *Classification by Structural Shape*

Proteins can be classified on the basis of their structural shapes:

- **Fibrous proteins** are made up of long rod-shaped or stringlike molecules that can intertwine with one another and form strong fibers.
  - insoluble in water
  - major components of connective tissue, elastic tissue, hair, and skin
  - e.g., collagen, elastin, and keratin.
- **Globular proteins** are more spherical in shape
  - dissolve in water or form stable suspensions.
  - not found in structural tissue but are transport proteins, or proteins that may be moved easily through the body by the circulatory system
  - e.g., hemoglobin and transferrin.

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## *Classification by Composition*

Proteins can also be classified by composition:

- **Simple proteins** contain only amino acid residues.
- **Conjugated proteins** also contain other organic or inorganic components, called **prosthetic groups**.
  - **nucleoproteins** — nucleic acids (viruses).
  - **lipoproteins** — lipids (fibrin in blood, serum lipoproteins)
  - **glycoproteins** — carbohydrates (gamma globulin in blood, mucin in saliva)
  - **phosphoproteins** — phosphate groups (casein in milk)
  - **hemoproteins** — heme (hemoglobin, myoglobin, cytochromes)
  - **metalloproteins** — iron (ferritin, hemoglobin) or zinc (alcohol dehydrogenase)

# Protein Structure

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## *Protein Structure*

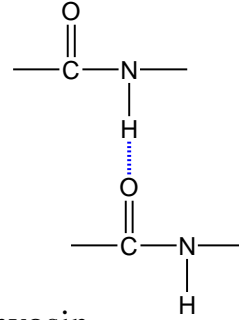
- The structure of proteins is much more complex than that of simple organic molecules.
  - Many protein molecules consist of a chain of amino acids twisted and folded into a complex three-dimensional structure
  - The complex 3D structures of proteins impart unique features to proteins that allow them to function in diverse ways.
- There are four levels of organization in proteins structure: primary, secondary, tertiary, and quaternary.

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## Secondary Structure — The $\alpha$ Helix

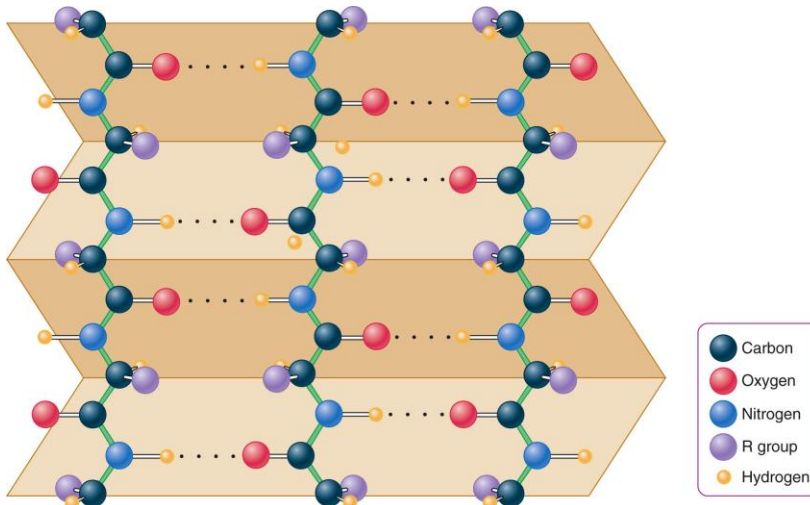
- The  $\alpha$ -helix is held in this shape by hydrogen bonding interactions between amide groups, with the side chains extending outward from the coil.
- The amount of  $\alpha$ -helix coiling in proteins is highly variable.
- In  $\alpha$ -keratin (hair, pictured below), myosin (muscles), epidermin (skin), and fibrin (blood clots), two or more helices coil together (**supracoiling**) to form cables. These cables make up bundles of fibers that strengthen tissues in which they are found:



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## Secondary Structure — The $\beta$ -Pleated Sheet

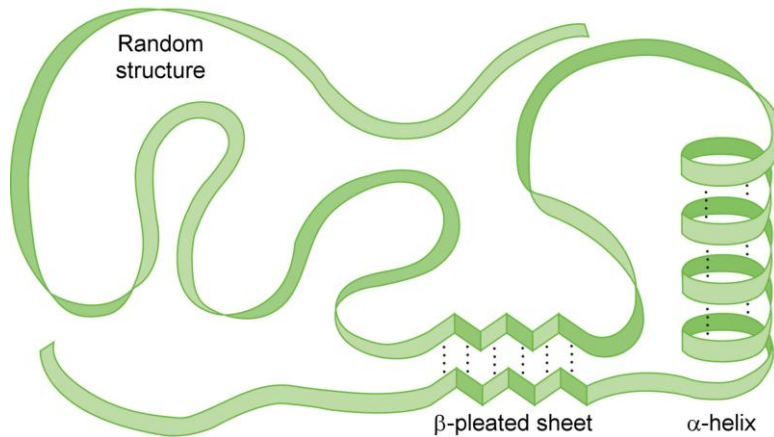
- Another secondary structure is the  **$\beta$ -pleated sheet**, in which several protein chains lie side by side, held by hydrogen bonds between adjacent chains:



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## Secondary Structure — The $\beta$ -Pleated Sheet

- The  $\beta$ -pleated sheet structure is less common than the  $\alpha$ -helix; it is found extensively only in the protein of silk.
- The figure below shows both types of secondary structures in a single protein.



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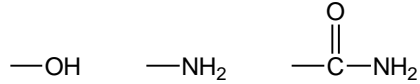
## Tertiary Structure of Proteins

- The **tertiary structure** of a protein refers to the bending and folding of the protein into a specific three-dimensional shape.
- These structures result from four types of interactions between the R side chains of the amino acids residues:
  1. **Disulfide bridges** can form between two cysteine residues that are close to each other in the same chain, or between cysteine residues in different chains. These bridges hold the protein chain in a loop or some other 3D shape.
  2. **Salt bridges** are attractions between ions that result from the interactions of the ionized side chains of acidic amino acids ( $-\text{COO}^-$ ) and the side chains of basic amino acids ( $-\text{NH}_3^+$ ).

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## *Tertiary Structure of Proteins*

- 3. Hydrogen bonds** can form between a variety of side chains, especially those that contain:



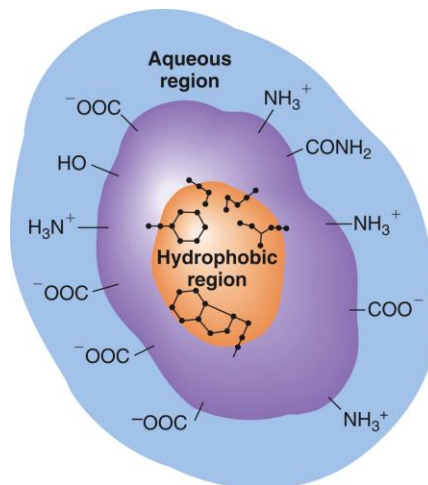
Hydrogen bonding also influences the secondary structure, but here the hydrogen bonding is between R groups, while in secondary structures it is between the C=O and NH portions of the backbone.

- 4. Hydrophobic interactions** result from the attraction of nonpolar groups, or when they are forced together by their mutual repulsion of the aqueous solvent. These interactions are particularly important between the benzene rings in phenylalanine or tryptophan. This type of interaction is relatively weak, but since it acts over large surface areas, the net effect is a strong interaction.

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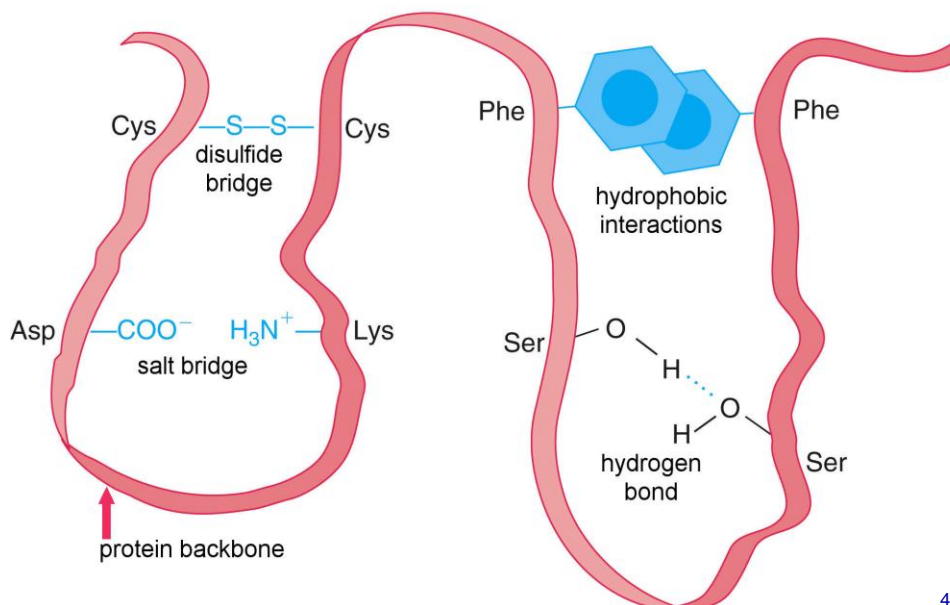
## *Tertiary Structure of Proteins*

- 4. cont.** The compact structure of globular proteins in aqueous solution, in which the nonpolar groups are pointed inward, away from the water molecules.



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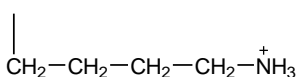
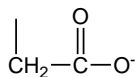
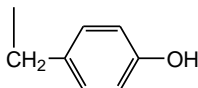
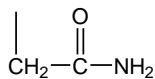
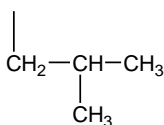
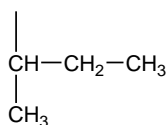
## Tertiary Structure of Proteins — Summary



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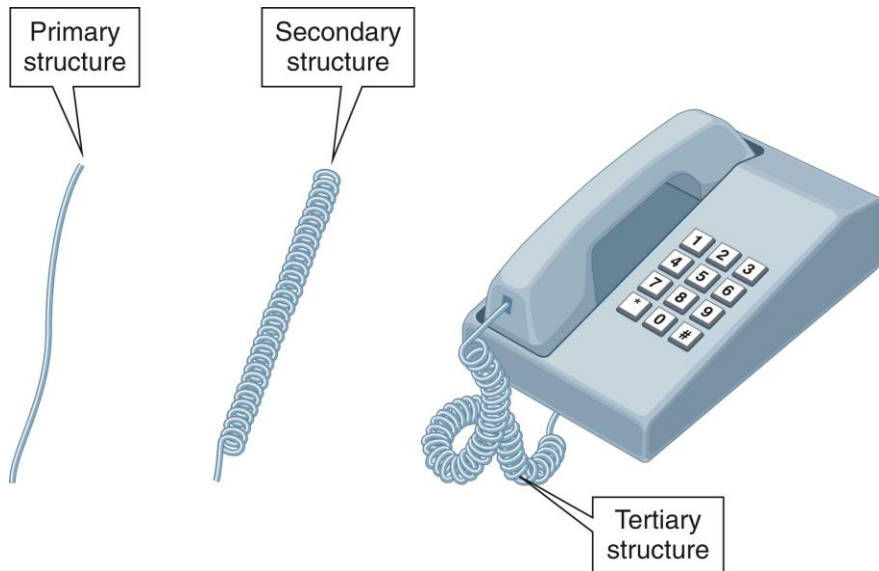
### Examples: R-Group Interactions

- What kind of R-group interaction might be expected if the following side chains were in close proximity?



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## *Visualizing Protein Structure*



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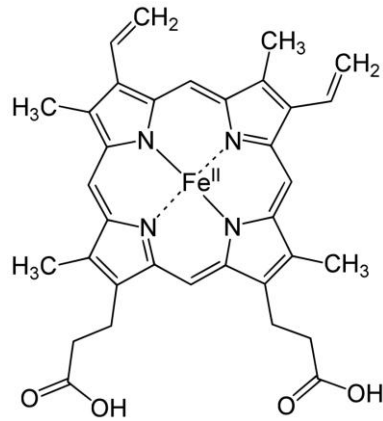
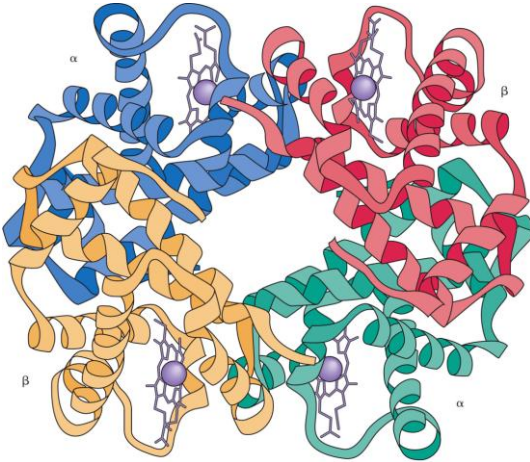
## *Quaternary Structure of Proteins*

- When two or more polypeptide chains are held together by disulfide bridges, salt bridges, hydrogen bond, or hydrophobic interactions, forming a larger protein complex.
- Each of the polypeptide **subunits** has its own primary, secondary, and tertiary structure.
- The arrangement of the subunits to form a larger protein is the **quaternary structure** of the protein.

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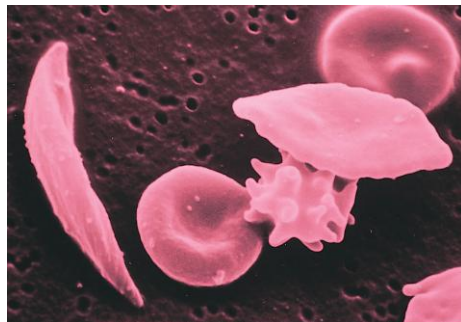
## Hemoglobin

- Hemoglobin is made of four subunits: two identical alpha chains containing 141 AA's and two identical beta chains containing 146 AA's. Each subunit contains a *heme* group located in crevices near the exterior of the molecule.



## Hemoglobin

- A hemoglobin molecule in a person suffering from **sickle-cell anemia** has a one-amino acid difference in the sixth position of the two  $\beta$ -chains of normal HbA (a glutamate is replaced with a valine).
- This changes the shape of red blood cells that carry this mutation to a characteristic sickle shape, which causes the cells to clump together and wedge in capillaries, particularly in the spleen, and cause excruciating pain.
- Cells blocking capillaries are rapidly destroyed, and the loss of these red blood cells causes anemia.

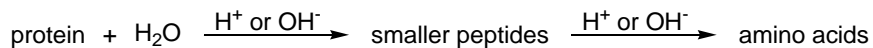


# Protein Hydrolysis and Denaturation

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## *Protein Hydrolysis*

- Amides can be hydrolyzed under acidic or basic conditions.
- The peptide bonds in proteins can be broken down under acidic or basic conditions into smaller peptides, or all the way to amino acids, depending on the hydrolysis time, temperature, and pH

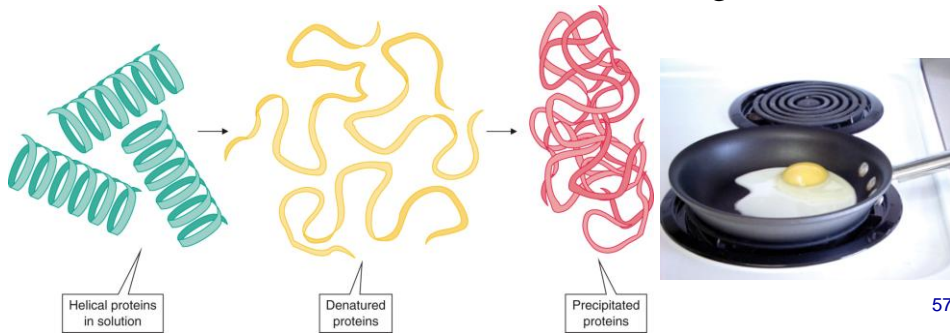


- The digestion of proteins involves hydrolysis reactions catalyzed by digestive enzymes.
- Cellular proteins are constantly being broken down as the body resynthesizes molecules and tissues that it needs.

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## Denaturation

- Proteins are maintained in their **native state** (their natural 3D conformation) by stable secondary and tertiary structures, and by aggregation of subunits into quaternary structures.
- **Denaturation** is caused when the folded native structures break down because of extreme temps. or pH values, which disrupt the stabilizing structures. The structure becomes random and disorganized.



## Denaturation

- Most proteins are biologically active only over a temperature range of 0°C to 40°C.
- Heat is often used to kill microorganisms and deactivate their toxins. The protein toxin from *Clostridium botulinum* is inactivated by being heated to 100°C for a few minutes; heating also deactivates the toxins that cause diphtheria and tetanus.
- Heat denaturation is used to prepare vaccines against some diseases. The denatured toxin can no longer cause the disease, but it can stimulate the body to produce substances that induce immunity.

## *Denaturation*

- Proteins can also be denatures by heavy-metal ions such as  $\text{Hg}^{2+}$ ,  $\text{Ag}^+$ , and  $\text{Pb}^{2+}$  that interact with  $\text{—SH}$  and carboxylate groups.
  - Organic materials containing Hg (mercurochrome and merthiolate) were common topical antiseptics.
  - Heavy-metal poisoning is often treated with large doses of raw egg white and milk; the proteins in the egg and milk bind to the metal ions, forming a precipitate, which is either vomited out or pumped out.

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## *Substances That Denature Proteins*

Substance or condition	Effect on Proteins
Heat and ultraviolet light	Disrupt hydrogen bonds and ionic attractions by making molecules vibrate too violently; produce coagulation, as in cooking an egg
Organic solvents (ethanol and others miscible with water)	Disrupt hydrogen bonds in proteins and probably form new ones with the proteins
Strong acids or bases	Disrupt hydrogen bonds and ionic attractions; prolonged exposure results in hydrolysis of protein
Detergents	Disrupt hydrogen bonds, hydrophobic interactions, and ionic attractions.
Heavy-metal ions ( $\text{Hg}^{2+}$ , $\text{Ag}^+$ , and $\text{Pb}^{2+}$ )	Form bonds to thiol groups and precipitate proteins as insoluble heavy-metal salts

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