THE HUMAN BODY
Its Structure & Physiology

FOURTH EDITION

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ITS STRUCTURE AND PHYSIOLOGY

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preface

The intense interest generated in both public and academic circles in environmental and health problems within the last five years has stimulated much research and study in the structure and function of the body and how the environment influences our normal function and structure. The present revision was made to reflect the rapid and continuing progress in physiology over the past five years and to maintain the text's status as the most up-to-date and comprehensive guide to our present knowledge of organ function and structure. The book is intended as an introduction to the subject of human structure and function for students at the sophomore level of college experience. Each chapter presents comprehensive coverage of the biochemical as well as the biological aspects of recent research in the many areas of physiology covered by the text. It is designed to suit the needs of the modern nursing and paramedical curriculum, as well as those of the beginning student in physiology, for whom the numerous recent references to original research papers will be invaluable. In general, the text will appeal to all students whose careers will be concerned with the living body.

As in previous editions, attention is focused on the cellular, subcellular, and molecular levels as well as the organ level to clarify the relationship between structure and function. Emphasis on the relationships and interlocking influences of the various organ systems will help the student grasp the fundamental principles of biological organization. The changes and additions in the fourth edition reflect the explosive proliferation of new knowledge in almost every area of physiology. The author has coordinated and synthesized wide areas of knowledge at a level he believes will be understandable to the serious student and teacher at the undergraduate level. Nevertheless, as the mathematical genius Louis LeCompt de Laplace said, "What we know is very little; what we do not know is immense." In the area of physiology, this is still true.

Extensive changes have been made in the chapters on the cell, the muscles, the circulatory and respiratory systems, and lipid and carbohydrate metabolism. Typical of the new material is the inclusion of recent work cited in the literature describing an hypothesis that accounts for the working of active transport through cell membranes. The most recent concepts of lung structure and function have been included. A new section on immune response cells shows that most antibody production requires the cooperation of thymus-derived lymphocytes and bone marrow-derived cells that produce antibodies. The allergic reaction is discussed in some detail, although simplified for a better understanding of hypersensitivity to products in the environment. The mechanism of alpha and beta adrenergic receptor action is a new part that we hope will clarify the action of the various catecholamines. In addition, many new summary tables, electron micrographs, and illustrations have been included to provide clarification and reinforcement of the text material.

The author has included pathology in many instances, as he believes that malfunction often points up more clearly how the organ system normally functions. In addition, the names of investigators and reference to their original research have been included to arouse curiosity about the ways of scientific thought.

contents

chapter one

the cell: physical and chemical structure

In order to understand the complex systems that the higher living organism represents, the biologist must resort to methods in which the system is broken down gradually from the whole animal to organ systems, to organs, to tissues, and finally to single cells, making thorough observations at every step and correlating function with the level of organization.

The cellular physiologist, attracted by the simpler interactions, prefers the lowest level of organization, the cell, as material for study. This is also a good starting point for all who are interested in studying the function and structure of animals; for the cell theory, which was formulated in 1839 by Schleiden and Schwann, tells us that all plants and animals are made up of cells and that all biological phenomena are cellular. In order to understand all functions, we must first understand function at the cellular level.

General characteristics of the cell

The term **cell** is rather difficult to define, because it represents an abstract generalization that attempts to cover a field that is too complex. It is possible, however, to give a general description that covers the majority of units of the cellular level of organization. First, we may make observations on the general characteristics of cells in regard to size and shape. In studying cells, the first thing

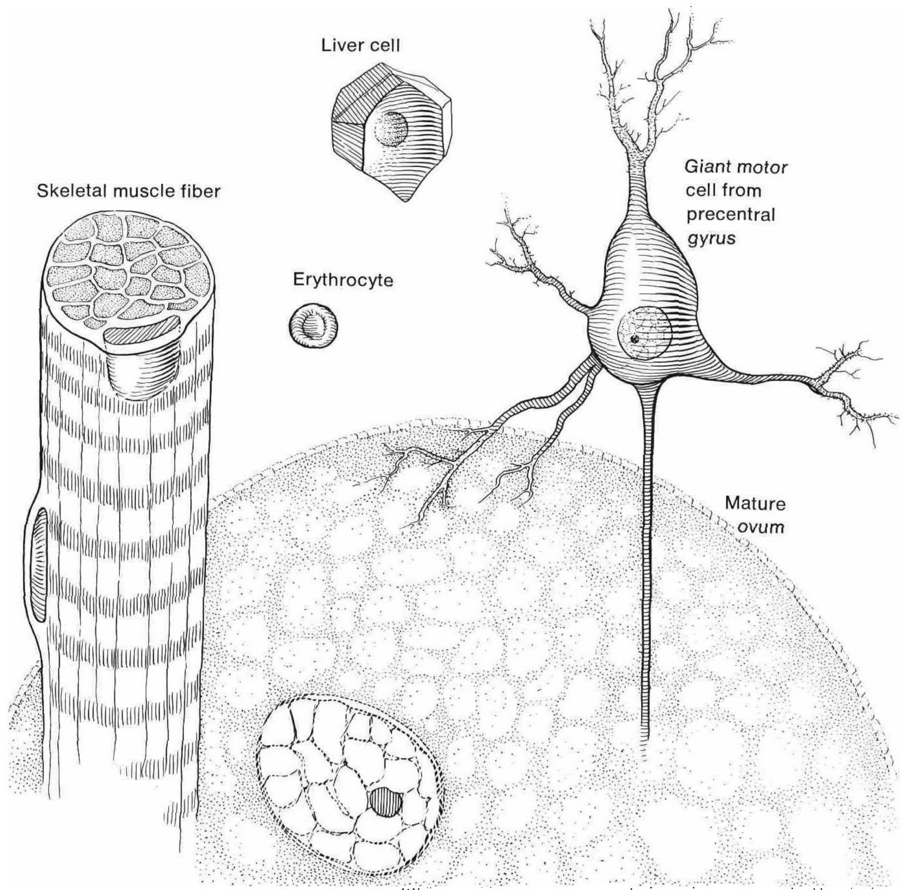


Figure 1-1. Variation in size and shape of various types of cells drawn to scale. Liver, 30 μm; erythrocyte 2×, 7.2 μm; giant motor cell of cortex 100×, 500,000 μm; mature ovum, 300 μm; skeletal muscle fiber 40×, 100,000 μm.

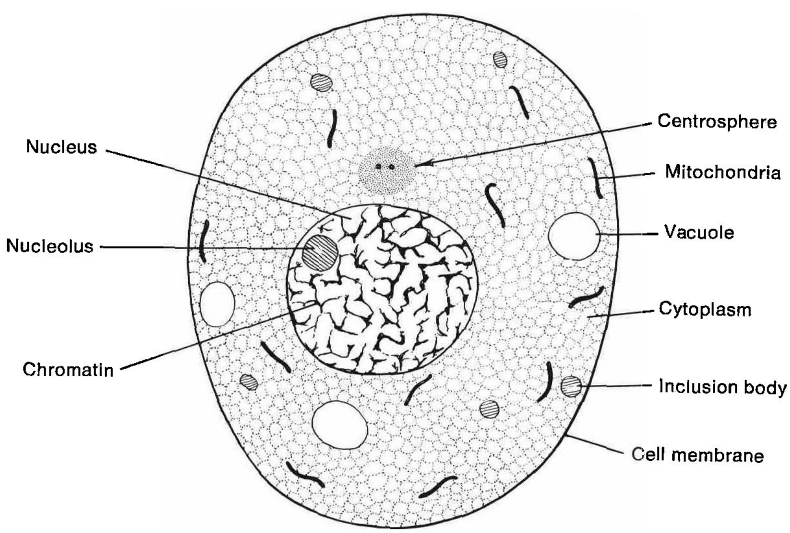


Figure 1-2. Typical architectural make-up of a cell as seen under the light microscope.

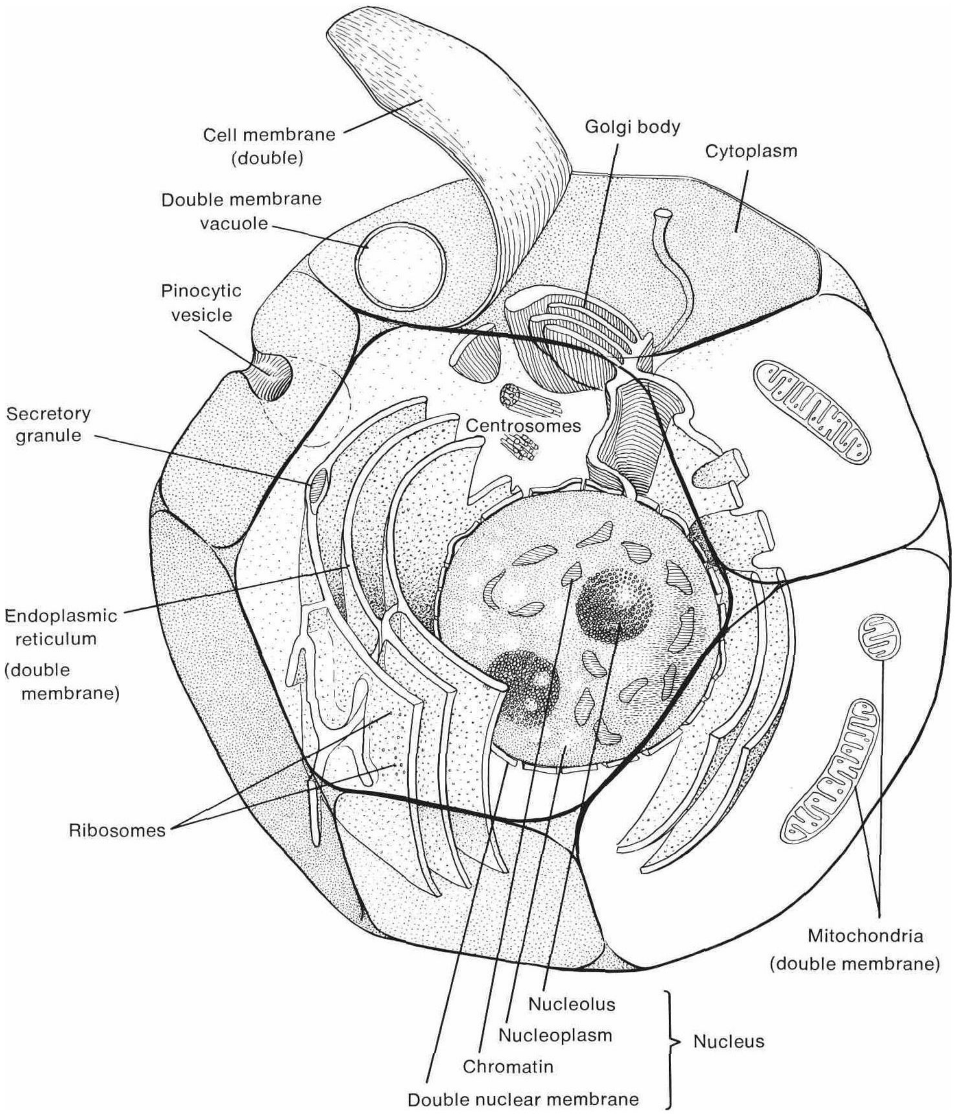
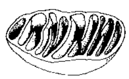
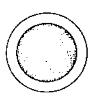


Figure 1-3. Architectural make-up of a cell as seen under the electron microscope.

we recognize is the great variation in size among different types of cells. Some cells are extremely small; in fact, there seem to be some bacteria that are invisible under the highest powers of the light microscope. Among organisms that have the smallest living mass are the microbes of the **pleuropneumonia group (PPLO),** which produce infectious diseases in various animals and man. They range in diameter from 0.25 micrometer (μm)—the limit in resolution of the optical light microscope—to 0.1 μm. They correspond in size to some of the large viruses. The average bacterium is a thousand times larger (diameter 1 μm). **PPLO** are a million times smaller than animal cells. Although most cells are microscopic in size, some are large enough to be seen without the use of specialized magnifying equipment;

these cells are considered macroscopic in size. The yolk of a hen's egg is a good example of such a cell, being about 1 inch in diameter.

Table 1-1. Important Structural Components of a Cell, and Their Functions

Structure	*Biochemical Composition*	*Function*
 Nucleus	Protein, deoxyribonucleic acid, ribonucleic acid	Transfer of information; formation of tRNA, mRNA, DNA; regulation of metabolism
 Nucleolus	Protein, ribonucleic acid	Important in metabolism of nucleus during stages of division; storage of tRNA
 Mitochondrion	Double lipoprotein membranous sac; phospholipids, cytochromes, flavoproteins	Energy released from carbohydrate, fat, protein stored as ATP
Golgi complex 	Complex of many foldings of lipoprotein membrane	Storage and secretion of fats
 Rough endoplasmic reticulum, Ribosomes	Double lipoprotein membranous channel in cytoplasm containing granules of ribonucleic acid	Channels for transfer of materials; synthesis of steroid; ribosomes—area of protein synthesis
 Lysosome	Double lipoprotein membranous sac—single unit, enzymes	Contains enzymes for splitting of lipid (lipases), protein (proteases), and nucleic acids (nucleases). Also phosphatases (split phosphate esters → monophosphate) glycosidases (split polysaccharides → monosaccharides)

The function that a cell must perform seems to have much to do with determining its size. Nerve cells acting as telegraph wires, picking up and sending electrical messages throughout the body, have to be extremely long. Female reproductive cells, which store food materials for sustaining a developing embryo for a long time, are relatively large and massive. Blood cells, which pass through minute tubules in the body, the capillaries, have to be extremely small. Even though we find this extreme variation in size of different kinds of cells, it appears to be a fundamental truth that the cells of any given tissue of a particular organism are nearly uniform in size and independent of the size of the mature individual. If we were to examine the cells that constitute the liver of a dog, we would find that all the cells of this organ are nearly uniform in size. If we compared these cells with the liver cells of some other organism, both specimens would be almost equal in size. The differences in the total mass of an organ are due to the number and not the volume of the cells (Driesch's law of constant cellular volume).

As we have found this great variation in size of different kinds of cells, so we will also find even a greater variation in the shapes of cells. Cells are closely packed together in the multicellular organism to form sheets of cells, called tissues, and because these cells are relatively soft, jellylike bodies, they are subject to the laws of mechanics and thus will form many-sided figures of various types. The shape of a cell will also be influenced by its function. The typical cell is spherical; thus, cells that usually exist alone, uninfluenced by pressures of surrounding cells, will demonstrate this spherical shape. Egg cells, blood cells, and some protozoa are examples of the typical spherical shape that cells assume. The reason for this is that

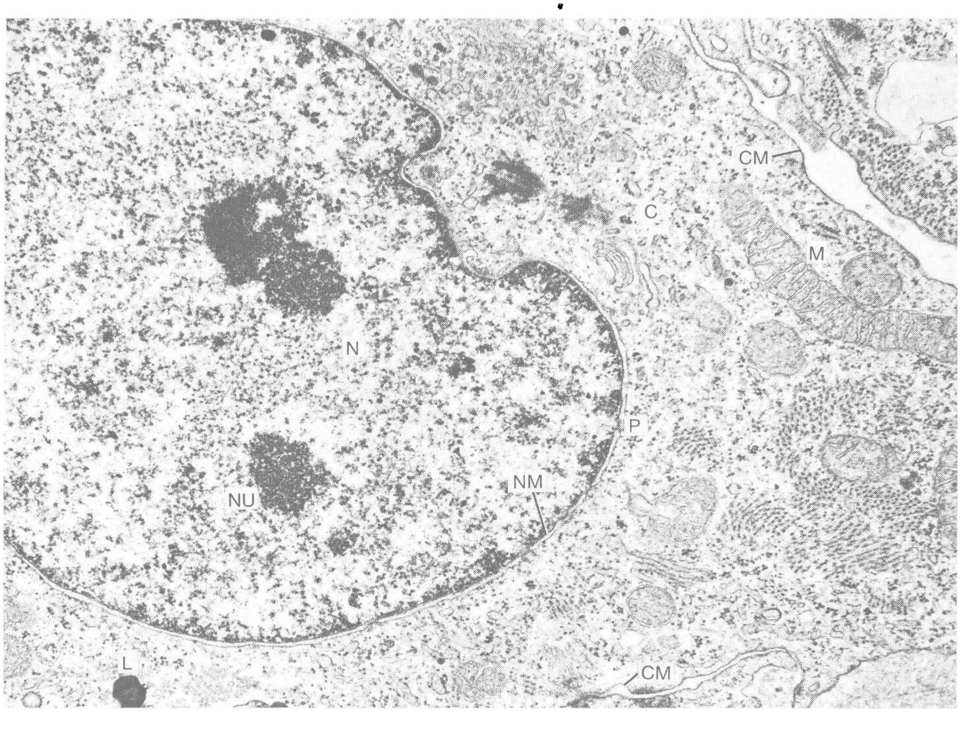


Figure 1-4. Electron micrograph of an animal cell revealing that the nuclear membrane is fenestrated and probably double. C, cytoplasm; CM, cell membrane; L, lysosome; M, mitochondrion; N, nucleus; NU, nucleolus; NM, nuclear membrane; P, pore of nuclear membrane. (Courtesy George D. Pappas, College of Physicians and Surgeons, New York, and The Upjohn Co., Kalamazoo, Mich.)

a fluid system, owing to the tension of the surface membrane, tends to assume the most compact form with the least possible surface exposed for a given mass. The sphere represents such a figure. Figure 1-1 (p. 2) shows some possibilities of variation in shape and relative size of cells.

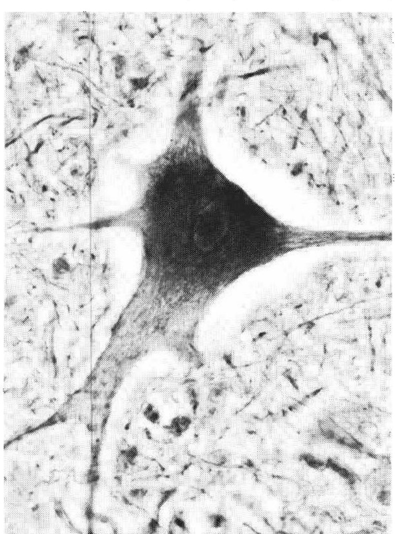
Structure of the cell

The typical architectural make-up of a cell includes a nucleus, surrounding cytoplasm, and a plasma or cell membrane (Fig. 1-2, p. 2). On closer examination and by using special techniques, other important structures may be identified (Fig. 1-3, p. 3 and Table 1-1). First let us consider the nucleus of a cell.

Nucleus

The **nucleus** appears as a more refractive intracellular sphere located somewhere near the center of the cell. Its protoplasm, usually referred to as the **nucleoplasm,** is separated from the protoplasm of the cell proper by the **karyotheca,** or **nuclear membrane** (Fig. 1-4). Scattered throughout the nucleoplasm of fixed preparations can be distinguished a series of twisted and interlaced filaments, the **chromonemata,** which contain a substance, **chromatin,** that stains intensely with certain dyes. Connecting the chromonemata are fine filaments, the **linin fibers.** One or more spherical bodies, the **nucleoli,** can be distinguished with appropriate methods of staining. We can see that the nucleus is not just a homogeneous mass of protoplasm but is a complex organization in itself, carrying out very specific functions for the cell and for the animal as a whole. In general, we can say the nucleus has some controlling influence on the activity of the cell, for all cells that engage in metabolic activity have a nucleus, and its absence is incompatible with a long and biochemically active life. The chromatin found in the nuclear material is concerned with the hereditary function carried out by the cell, for it is this material that forms the chromosomes, which, in turn, carry the genes.

Figure 1-5. Section through spinal cord of mammal showing neurofibrillae in nerve cell. (Courtesy Ward's Natural Science Establishment, Inc., Rochester, N.Y.)



Chemical analysis has shown that chromatin consists of four major macromolecules: a low molecular weight protein, a more complex protein, deoxyribonucleic acid (DNA), and ribonucleic acid (RNA). Studies have shown that DNA is the key molecule that enables chromatin to function as the hereditary unit within the cell. Caspersson and Schultz have demonstrated that the nucleolus contains ribonucleic acid, probably in the form of nucleoprotein. Ribonucleic acid plays an important role in the metabolism of the nucleus during the stages of division and of protoplasmic growth. The function of the **nucleolus** and, particularly, the significance of the cyclic changes that it undergoes during mitotic activity are still open to interpretation. More recent evidence indicates that the nucleolus receives certain types of RNA synthesized from the DNA in the nucleus and surrounds that RNA with a protein coating which is synthesized by the nucleolus thus forming ribosomal RNA (rRNA). Thus, it appears that the nucleolus is responsible for the synthesis of ribosomal protein and of ribosomal assemblage. Studies with anucleolate cells show that ribosomal formation cannot take place and that a cell without a nucleolus loses its ability to synthesize proteins and other substances upon which it depends for its survival (Brown and Gurdon, 1964).[1]

[1] Brown, D. D. and Gurdon, J. B. Absence of ribosomal RNA synthesis in the anucleolate mutant of Xenopus Laevis. *Proc. Natl. Acad. Sci., U.S.A.*, **51:**139–46 [20, 105], 1964.

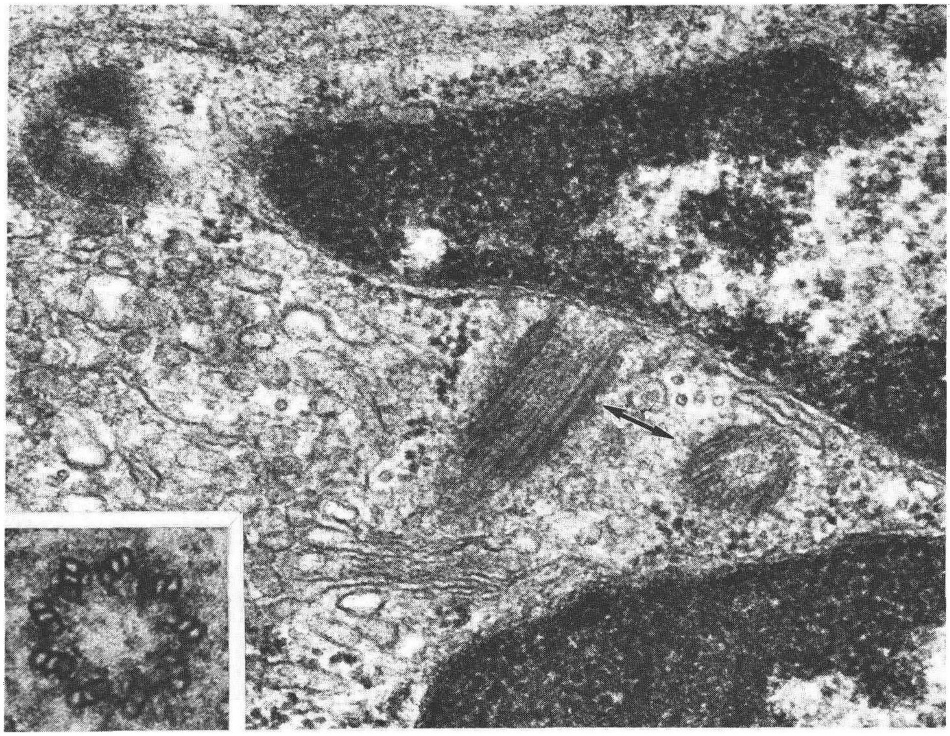


Figure 1-6. The centriole, magnified 30,000×. Two or more centrioles are found in cells that retain the potential to divide. The two centrioles in the electron micrograph (arrow) from rat kidney cell are sectioned obliquely. A series of parallel lines is visible in the long axis in each centriole. Inset. A cross section of a centriole demonstrates that the parallel line structures are 27 microtubules arranged in nine triplets. Each of the microtubules within the triplet shares its wall with the adjacent tubule. (Courtesy Timothy K. Maugel, Electron Microscopy Laboratory, Department of Zoology, University of Maryland, College Park, Maryland.)

Cytoplasm

Commonly, the protoplasm found surrounding the nucleus and limited on its outer periphery by the cell membrane is referred to as the **cytosomic protoplasm,** or **cytoplasm,** to differentiate it from the nucleoplasm. Here again we find that, on more specific qualitative examination of the cytoplasm, many formed constituents can be found. These are divided into **organoids (organelles)** and **inclusions.** The organoids are closed membranous structures capable of self-perpetuation, which would indicate they are specialized particles of living substance. They include such structures as fibrils, tubules, cilia and flagella, centrioles, mitochondria, lysosomes, and Golgi apparatus. In plant cells another important living structure in the cytoplasm are the plastids. The inclusions are nonliving substances in cytoplasm but are necessary for its normal physiological activity. They consist of accumulations of lipids, carbohydrates, proteins, pigments, secretory granules, and crystals. A characteristic inclusion found only in mature plant cells is the **vacuole,** a clear structure in the central region of the cell (Fig. 1-2) filled with a watery solution the **cell sap.**

Organoids (organelles). **Fibrils** are thin protoplasmic threads running through and confined to the protoplasm. In many cells they are referred to as **tonofibrillae** and are presumed to offer stability to the cell. In muscle and nerve cells the fibrils are very highly developed and are referred to as myofibrillae in the former and neurofibrillae (Fig. 1-5) in the latter. They are concerned directly with contraction

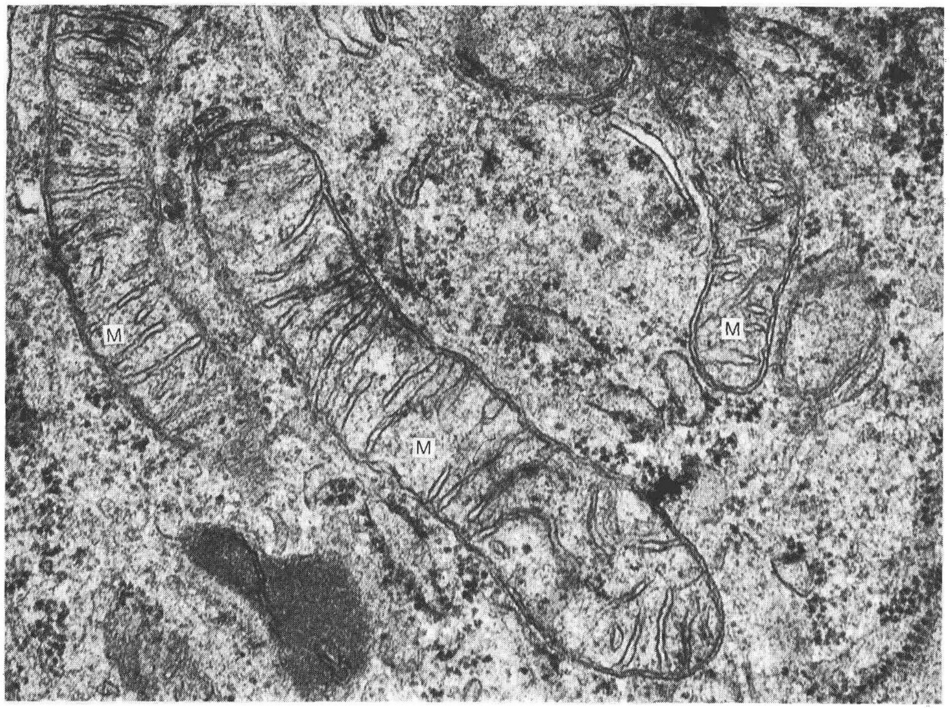


Figure 1-7. Electron micrograph of pancreatic exocrine cell. The edge of the nucleus is at the bottom; several round or oval profiles of mitochondria are scattered across the picture from lower right to upper center. The parallel rows occupying the space between are elements of the endoplasmic reticulum. (Courtesy G. E. Palade, The Rockefeller Institute for Medical Research, New York, and The Upjohn Co., Kalamazoo, Mich.)

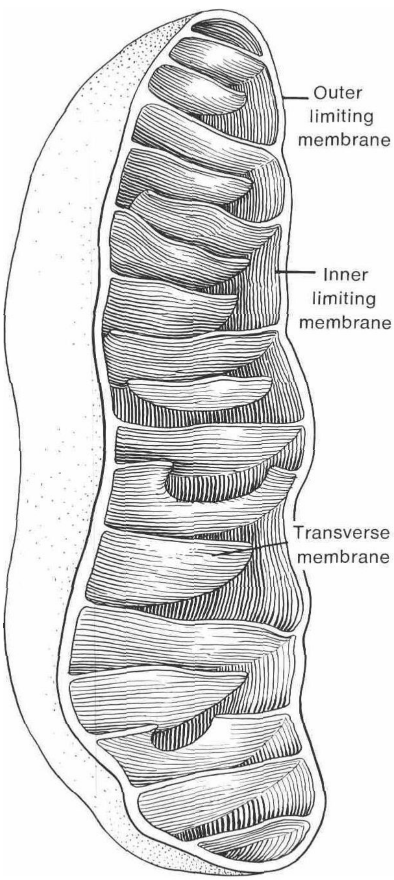


Figure 1-8. Schematic representation of a mitochondrion.

in muscle cells and conduction in nerve cells. **Centrioles** appear as small dots in a clear area of cytoplasm known as the **cell center,** or **attraction sphere,** which is very closely associated with the nucleus but not found in it. The centrioles are believed to initiate mitotic activity. The structure of the centriole is similar to the structure of the basal body (Fig. 1-6).

Mitochondria. The **mitochondria** are common to all higher animal and plant cells and can be easily demonstrated when the stain Janus green B is applied to the tissue. They may be described as granular, rod shaped, or filamentous; that is, they are pleomorphic bodies continually changing shape and position in the living cell.

The structure of the mitochondria has been clearly revealed by the electron microscope (Fig. 1-7). A double lipoprotein membrane, similar to the nuclear and cytoplasmic membrane, surrounds the individual mitochondria. The inner membrane is thrown into many fingerlike projections toward the interior to provide a greater surface area (Fig. 1-8). The mitochondrion functions to oxidize the simple forms of proteins, fats, and carbohydrates that are delivered to the cell by the organism (that is, amino acids, fatty acids, glucose) into carbon dioxide and water or into a smaller acid or alcohol. The energy released in this process is transferred into the production of a high energy phosphate compound known as **adenosine triphosphate** (ATP). This molecule is then secreted back into the cytoplasm and utilized in the cell whenever energy is needed.

It has recently been shown that mitochondria contain DNA in the form of a single closed loop. Chloroplasts in plant cells contain a similar form of DNA, as do bacteria and a number of viruses. Particles of ribonucleic acid, ribosomes, have also been found in mitochondria that are quite similar to those found in bacteria, other prokaryotic cells, and viruses. This has led to the speculation that the origin of mitochondria and chloroplasts within eukaryotic cells were initially derived from primitive organisms that invaded the early primitive eukaryotic cells and set up a symbiotic relationship. Whether this is scientifically valid or not is not important here; it does remain that the DNA found in mitochondria is different from that found in the nucleus, which indicates that mitochondria somewhat control their own heritable qualities. The number of mitochondria present within a cell varies with the type cell, its size, and its specific energy requirement. An animal cell might have on the order of 1000 mitochondria, whereas plant cells of similar size have relatively few.

Lysosomes

Lysosomes (Fig. 1-9) are oval shaped bodies possessing a relatively simple single unit limiting membrane and filled with powerful lytic enzymes that can break down a variety of chemical components of which other membranous structures are composed and other large molecules. Lysosomes are found in all eukaryotic cells and are identified by the presence of a single unit membrane and a positive staining reaction for acid phosphatase or other known lysosome-related enzymes.

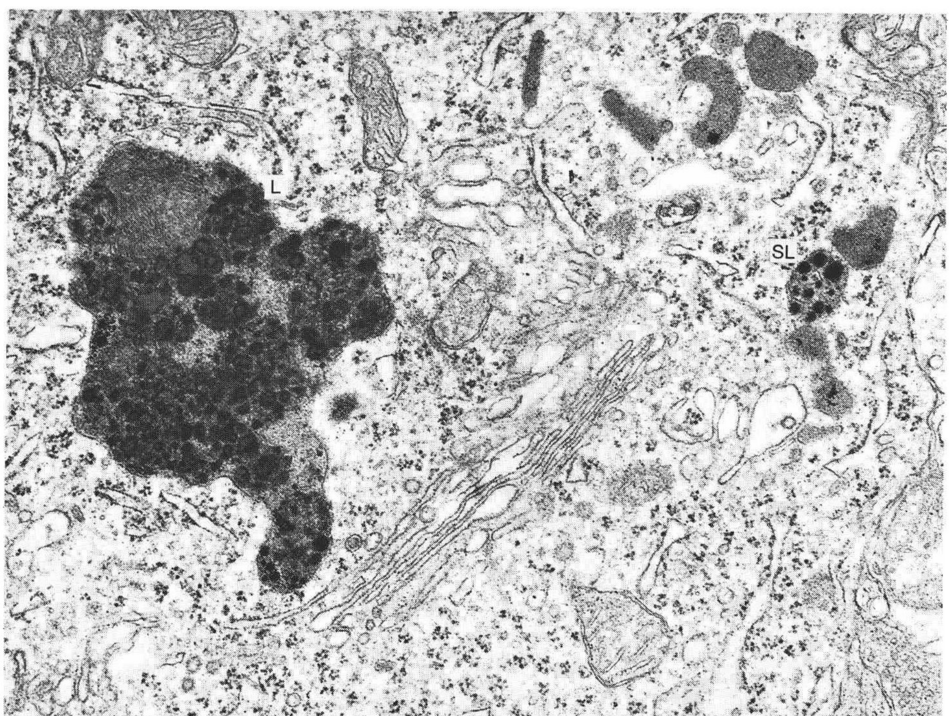


Figure 1-9. Lysosomes are present in most cells but are particularly abundant in white blood cells and macrophages. The powerful lytic enzymes contained within the lysosome are effectively separated from the cytoplasm by the special double membrane surrounding the structure: L, large phagocytic lysosome; SL, young lysosome. (Courtesy Timothy Maugel, Electron Microscopy Laboratory, Department of Zoology, University of Maryland, College Park, Md.)

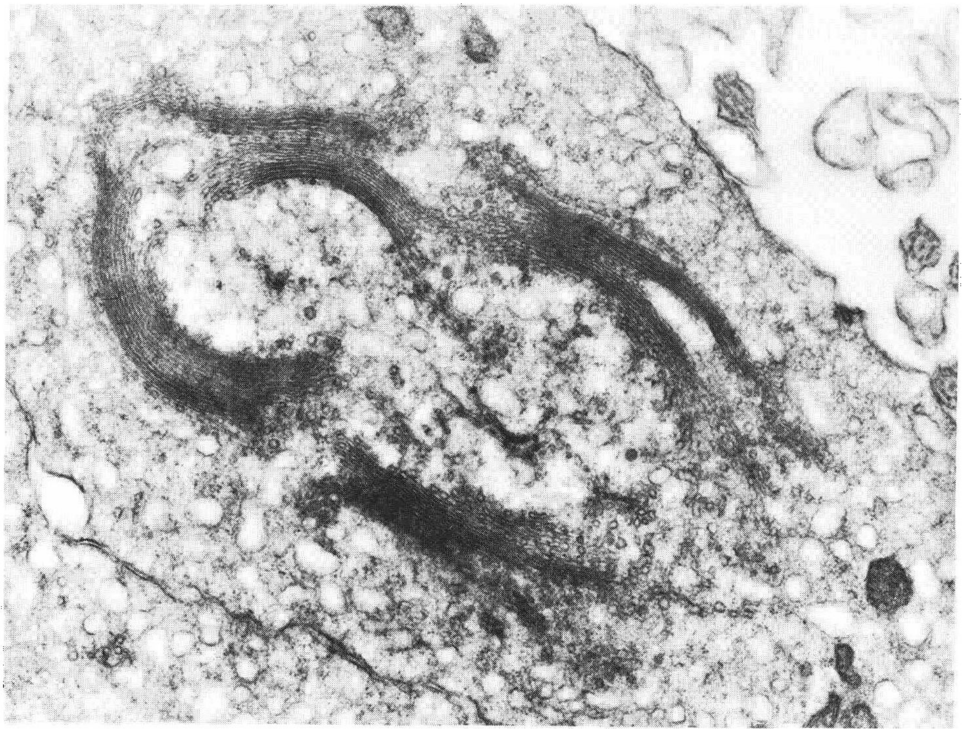


Figure 1-10. Electron micrograph of animal cell showing the Golgi complex. (Courtesy L. E. Roth, Iowa State University, Ames, Iowa, and The Upjohn Co., Kalamazoo, Mich.)

More than 30 enzymes have now been associated with the lysosome[2] and this complex is potentially capable of hydrolyzing virtually all of the major constituents of protoplasm. In fact it is now clear that lysosomes form an intracellular digestive system and are especially rich in those cells that have phagocytic activity. It is the lysosomes of these cells that are capable of taking in worn-out cellular components and denatured molecules, degrading them and returning them to the cytoplasm for use in resynthesis. This protective role is probably the most important function of lysosomes in multicellular organisms. In unicellular organisms it appears that the main function of lysosomes is that of nutrition, whereby large molecules are taken into the cell and degraded into smaller utilizable fragments—a true digestive function.

The most common enzymes found in the lysosome are the following: acid hydrolases (splitters of acid), acid phosphatase, β-glucuronidase, acid ribonuclease, acid deoxyribonuclease, and cathepsin D (see Table 1-1).

Golgi apparatus. The **Golgi apparatus** generally can be made visible by using an osmic acid and silver impregnation technique (Figs. 1-10 and 1-11). It appears as an irregular reticulum, situated around the centrosphere (central body). This

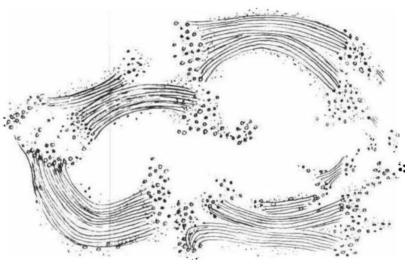


Figure 1-11. Schematic representation of Golgi complex.

[2] A. L. Tappel, "Lysosomal Enzymes and Other Components." In *Lysosomes in Biology and Pathology,* Vol. II. New York, American Elsevier Publ. Co., Inc., 1969.