ANATOMY AND PHYSIOLOGY

An Illustrated Guide

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Foreword

The world runs on the successful interlocking of systems. Electricity, transportation, waste management, and air quality all depend on systems working together to run cities and countries. Anyone who wants to understand how a civilization survives sooner or later comes to grips with the integration of systems.

It is no different when it comes to the study of living things. The analysis of the inner workings of organisms, be they plants or animals, requires an appreciation of anatomy and physiology—the forms and functions of life. These scientific disciplines comprise the keys to biological knowledge, helping to develop a broad view of how organisms, no matter how distantly related, cope with the dictates of reproduction, feeding, excretion, gas exchange, locomotion, and a host of other activities that characterize life on Earth. The old adage that "form follows function" is no better expressed than in the diversity of physiological responses that animals and plants have evolved as adaptations to environmental factors. What is striking about these adaptations is not just the fascinating array of solutions that have come and gone over time, but the remarkable number of times that organisms hit upon similar answers to similar situations, even though the organisms involved might be very distant from one other on the tree of life. Life forms as different as grasses, sponges, and birds all need to meet the requirements of producing the gametes used in sexual reproduction. Skeletal systems support sea urchins, corals, and cats. The challenges of gas exchange and respiration in water and in air have been met by fish, beetles, and the leaves of all sorts of plants.

Anatomy and Physiology: An Illustrated Guide introduces the world of physiological systems in a brilliantly illustrated and comprehensive way. Like street maps of cities, the sections of this work lead through the twists and turns of life's inventiveness, telling the stories of how physiological systems operate. With carefully researched text and detailed drawings reviewed by experts in the field, these articles make it easy to follow how each system works and contributes to the lives of organisms. The latest concepts in physiological science, including recent and remarkable advances in genetics and organic development, are clearly laid out for the student and expert alike. As a resource for coursework or simply for taking an informative tour through the organismal neighborhood, *Anatomy and Physiology* will be an indispensable companion.

Richard Mooi
Richard Mooi is Curator of Echinoderms at the California Academy of Sciences, San Francisco

The articles on biological systems included in this work are also available by subscription online from Marshall Cavendish Digital at www.marshallcavendishdigital.com as part of a larger encyclopedic work, *Animal and Plant Anatomy*, which also contains more than 80 additional articles on the anatomy of particular organisms.

Cell biology and genetics

All living things have two goals: to survive and to reproduce. The smallest unit of life is the cell, and cells also have these goals. The sciences of cell biology and genetics examine how cells survive and reproduce.

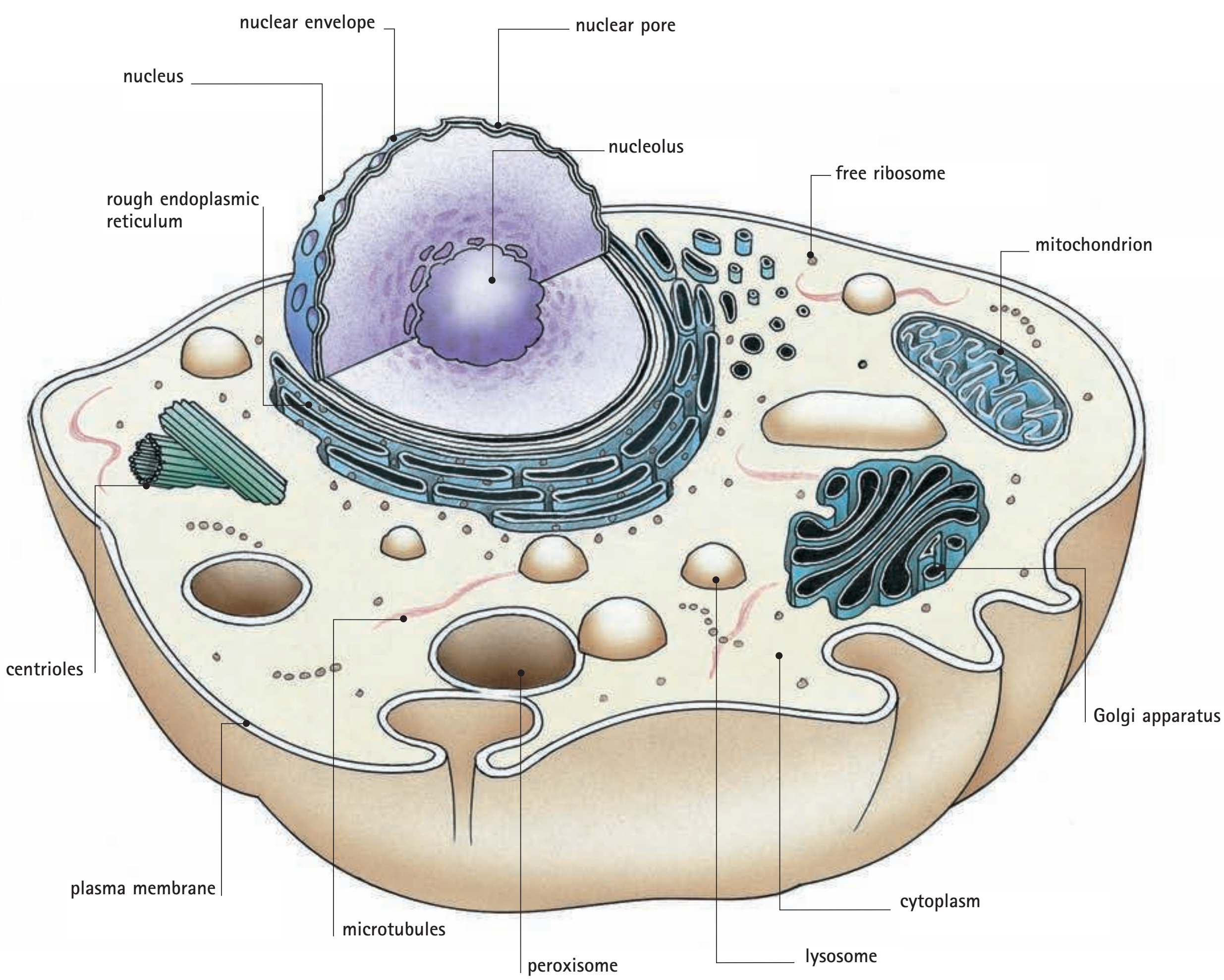
Living things are grouped into two major categories, called prokaryotes and eukaryotes, depending on the basic structure of their cells. Bacteria are prokaryotes, and all other living things, including plants, animals, fungi, and protists, are eukaryotes.

Single-celled organisms, including bacteria and simple eukaryotes such as amoebas, ciliates, and various algae, are interesting to biologists because they manage to accomplish all the tasks required to sustain life using one multipurpose cell. In multicelled organisms, different cells tend to be specialized for different roles, such as acquiring food, using energy, eliminating waste, avoiding harm, and producing offspring. The shape and structure of cells depend on what functions a cell has to accomplish. How cell structures are made is defined by genes, which contain instructions for making proteins. Proteins are immensely diverse molecules that contribute to both the structure and the functioning of the cell. A group of proteins known as enzymes act as enablers, or catalysts, in a vast number of important chemical reactions. Without them, the processes of life would grind to a halt.

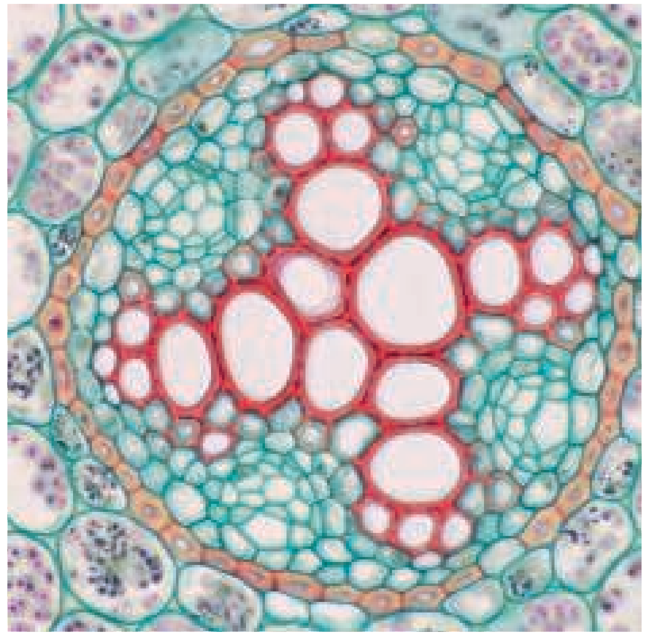
What are cells made of?

Cells are made of four major types of macromolecules, or large molecules: proteins, carbohydrates, fats (also known as

▼ *An animal cell contains many organelles that together enable it to eat, grow, reproduce, and fight off invaders.*



lipids), and nucleic acids. In general, proteins are the active components of the cell, performing most of the functions essential to life. Carbohydrates embellish the proteins, modifying and fine-tuning them to do specific jobs and helping provide structure to the cell itself. Lipids, which are more malleable than proteins or carbohydrates, make up the outer layer of cells. Nucleic acids carry information for manufacturing all of the molecules within cells. Deoxyribonucleic acid (DNA), which contains the sugar deoxyribose, stores this information, like a recipe book for the cell. Ribonucleic acid (RNA) contains the sugar ribose. When a cell needs to make a particular protein, RNA accesses the necessary information coded in the DNA and translates it into a form recognized by the protein-building components of the cell.



▲ *This cross section of a buttercup root shows the different types of cells stained for clarity. The xylem cells (red) are used for transporting water, and the phloem cells (green) are used for transporting nutrients. Surrounding these are the pericycle (yellow), involved in the formation of lateral roots; and the cortex (large green cells), used for storage of nutrients.*

The beginnings of life

How did life get started? Scientists have studied the chemical conditions they think existed on Earth many millions of years ago and found evidence that RNAs may have been present. This discovery caused some excitement because RNA can store genetic information and it can act as an enzyme, called a ribozyme. Enzymes, most of which are proteins, are molecules that enable chemical reactions to occur. Chemical reactions underlie almost all processes in living organisms, including those necessary for survival and reproduction. Thus RNA may have been the first molecule that not only was able to perform the chemical reactions necessary for life (survival), but also could pass on genetic information (reproduction).

While RNA may be the molecule with which life began, it is still unclear how the next step took place. How did a chemical reaction become a living, biological entity? One can imagine that molecules acting together can accomplish more tasks than those acting alone, and the simplest life-forms must have evolved from groups of molecules working together. Very simple cells, such as bacteria, are enclosed bundles of chemical reactions that can use energy to acquire food, eliminate waste, move, and reproduce. The reactants are enclosed within a malleable balloonlike container—the cell membrane—and a tough structure that provides protection and physical support: the cell wall. More complex life-forms evolved when groups of cells began to work together.

FEATURED SYSTEMS

CELLS AND THEIR FUNCTIONS Cells have many differing structures that help them accomplish their unique functions. *See pages 8–9.*

CELL EXTERNAL ANATOMY The cell membrane encloses the cell contents and selectively allows molecules to pass in and out of the cell. *See page 10.*

CELL INTERNAL ANATOMY Eukaryotic cells have organelles, such as the nucleus and mitochondria, that carry out the various functions of the cell. *See pages 11–16.*

MOVEMENT AND SUPPORT The cytoskeleton provides support for the cell and pathways for cell molecules. Flagella and cilia enable the cell to move. *See page 17.*

GENES AND INHERITANCE Long strands of DNA carry genes. DNA forms chromosomes, which provide the genetic (inherited) information organisms need to construct cells. *See pages 18–21.*

NUCLEIC ACIDS: RECIPES FOR CELLS Nucleic acids are used by cells to provide information for making all the cell's molecules. The nucleic acids are ribonucleic acid (RNA) and deoxyribonucleic acid (DNA). *See pages 22–25.*

THE CELL CYCLE AND CELL DIVISION Cells can reproduce by cell division in a process called mitosis. Sometimes this form of cell division becomes uncontrollable and results in cancer. *See pages 26–29.*

Cells and their functions

CONNECTIONS

COMPARE the cells of a mammal, such as a ***HIPPOPOTAMUS***, with those of a nonmammalian vertebrate such as a ***JACKSON'S CHAMELEON***. In mammals the cells do not possess a nucleus, but in other vertebrates they do.

Cells in multicellular organisms specialize to become different in structure and function. For example, animal nerve cells, called neurons, transmit information gathered from all around the body and from the outside world to the brain, and then trigger an appropriate response. Specialized neurons receive different kinds of information from various sense organs: visual information through eyes or light-sensitive cells; sound information through ears; touch information from whiskers or skin; and chemical information such as taste and smell. Chemical receptors are located in the mouth and nose of most vertebrates but may be mounted on antennae or scattered all over the body surface in other animals. Some animals have additional senses, for example for detecting vibrations, electrical signals, or magnetism. However, regardless of its source, all sensory information is ultimately processed by some part of the nervous system, and neurons are specialized to do the job as quickly and efficiently as possible.

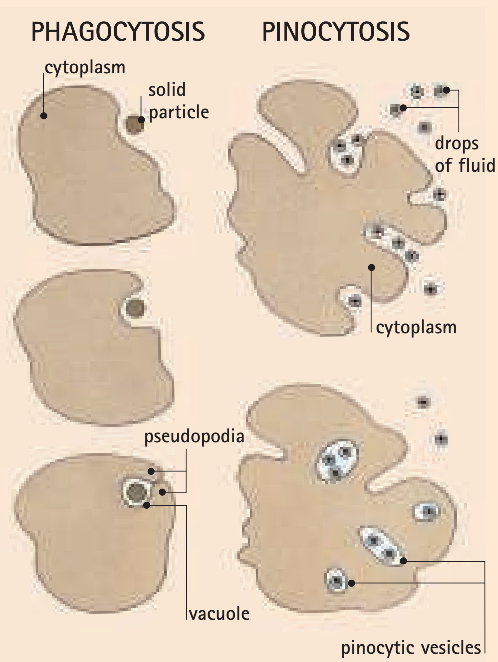
Muscle cells

Differentiation is the process by which cells become specialized. Neurons are just one example, and muscle cells are another. Muscle cells, or myocytes, make proteins that allow the cells to contract. When muscle cells work together, they can generate movement on a much larger scale—that of the whole muscle or whole animal. Humans and other vertebrates have three types of muscle cells: skeletal, smooth, and cardiac. Skeletal muscles are attached to the skeleton and move the torso and limbs. As skeletal muscle cells form, they align to create long linear fibers, hence their alternative name: striated (or striped) muscle. Skeletal muscle cells also fuse to create larger

IN FOCUS

How cells eat

All cells need to harvest macromolecules to provide the building blocks of their own proteins, carbohydrates, fats, and nucleic acids. Cells also need energy to assemble and disassemble these molecules. Autotrophs, or "self-feeders," can create their own macromolecules from inorganic raw materials, such as carbon dioxide, water, and light energy. Plants and bacteria that use photosynthesis to construct sugar and other molecules are autotrophs. Animals and fungi are heterotrophs, which obtain macromolecules and energy by eating or decomposing the tissues or cells of other organisms. All heterotrophs are ultimately dependent on autotrophs for food, and the vast majority also depend on oxygen, a byproduct of photosynthesis.



▶ *In phagocytosis, large solid particles are enclosed by folds of the plasma membrane. In pinocytosis, the membrane folds inward, beneath the molecule, enclosing dissolved material.*

cells with many nuclei, which contract in one dimension. Smooth muscle cells are found in the walls of the stomach, intestines, and blood vessels. These cells are smaller and less organized than skeletal muscle cells and contract in waves. Cardiac muscle cells assemble to form the heart, which contracts repeatedly and without tiring to pump blood around an animal's body.

The sex cells

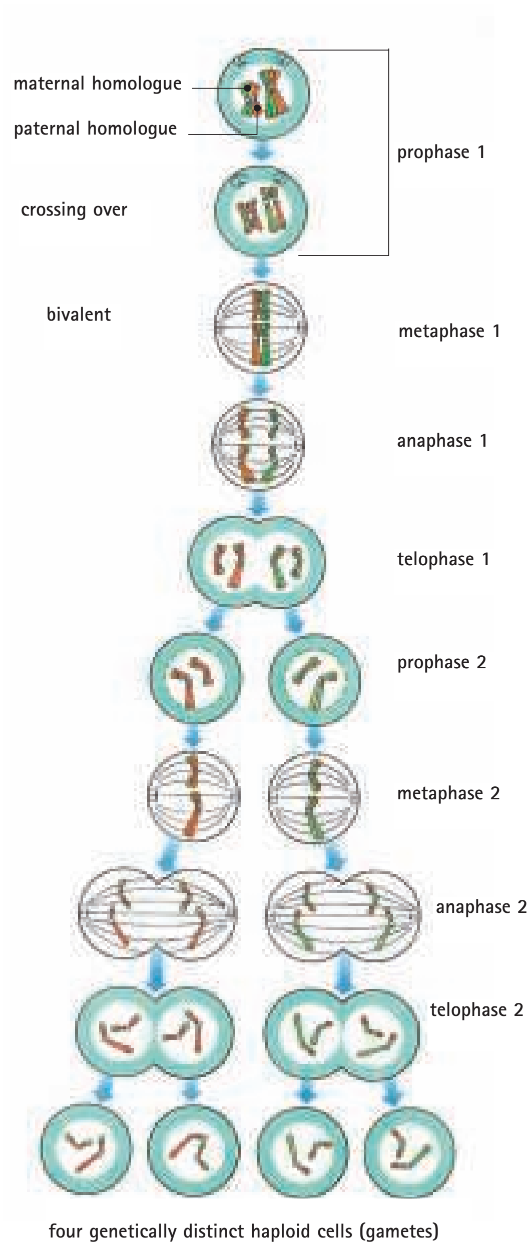
Sex cells, or gametes, are specialized to create offspring. Male gametes, called spermatozoa or sperm, have a tail called a flagellum (plural, flagella) that helps them move to find an egg for fertilization. Female gametes, called eggs or ova (singular, ovum), are typically large and carry nutrients and energy to sustain the zygote, or fertilized egg, at the beginning of development. Both eggs and sperm are haploid, carrying only half the DNA normally needed by a new individual. When each contributes its DNA to the zygote, the zygote is then diploid, having two copies of each chromosome. If sex cells were diploid, the next generation would have four sets of instructions (tetraploid), the next would have eight copies (octoploid), and so on. Meiosis is the process of cell division by which the number of DNA-containing structures, called chromosomes, is halved to produce haploid gametes.

Guard cells

Other cells guard against damage. Epithelial cells cover all surfaces in the human body, holding organs and tissues together and protecting them from invaders like bacteria and viruses. Epithelial cells also cover internal surfaces such as the respiratory tract, from the nostrils to the lungs; and the digestive tract, from the mouth to the stomach, intestines, and anus. Skeletal tissues, such as bones and cartilage, guard against damage by giving the body structure and protecting internal organs. For example, the rib cage protects the heart, lungs, and liver; and the skull and vertebrae protect the brain and spinal cord.

Plant cells

Plants also have specialized cells. Parenchyma cells in leaves contain chloroplasts that gather light energy and use it to manufacture the sugar glucose from carbon dioxide and water using a process called photosynthesis. Parenchyma cells in the stem and roots store starch. Collenchyma and sclerenchyma cells help provide structural support. Collenchyma cells are stiff but flexible, and are found in younger plants because they give the plant structure without restricting its growth. Sclerenchyma cells are less flexible and are found in older plants. Vascular plants also contain two sorts of conducting tissues: xylem, which carries water from the roots to the rest of the plant; and phloem, which moves food molecules throughout the plant.



◀ MEIOSIS
Each chromosome is made up of a pairing of a paternal homologue (from the father) and a maternal homologue (from the mother). At prophase 1, the chromosomes duplicate, forming X-shaped chromosomes. During a process called crossing over, the chromosomes that form these pairs exchange some genetic material. Telophase 1 produces two new cells containing half the full complement of chromosomes: that is, they are haploid. In prophase 2 onward there is no duplication of DNA. The subsequent phases result in the production of two sibling chromatids, which separate to produce four distinct haploid offspring cells. When a male gamete (sperm) fertilizes (fuses with) a female gamete (egg or ova) the resulting cell, or zygote, has two sets of chromosomes; so, it is diploid.

Cell external anatomy

Cells have specialized structures depending on their functions. All cells are surrounded by a cell membrane that acts like a sack to contain the cell contents. The cell membrane also selects which molecules can move into and out of the cell, keeping out toxic materials and bringing in nutrients and beneficial molecules. In addition to the cell membrane, plant cells have a rigid cell wall, which protects against damage and maintains the plant's structure.

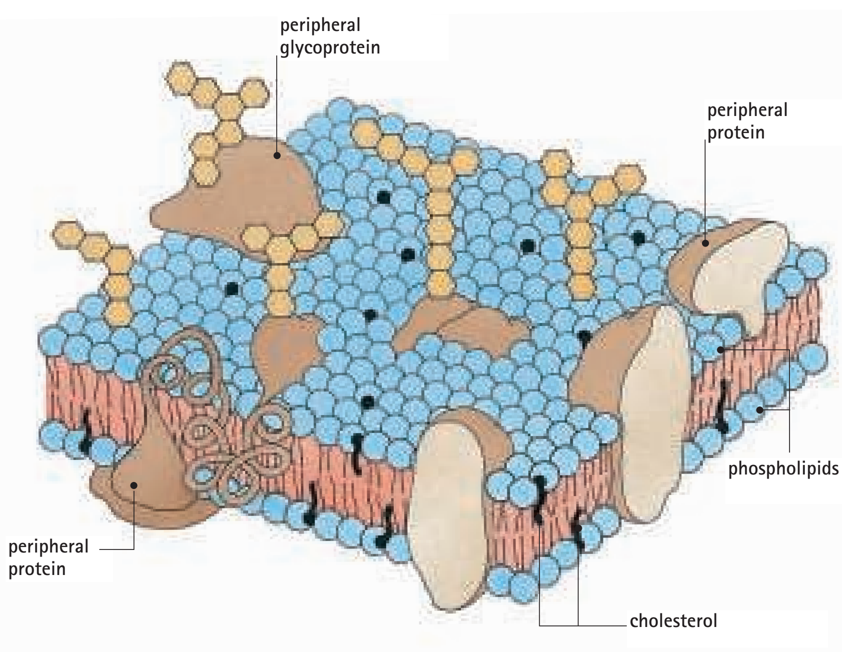
A cell's shape is tailored to its function. For example, the chains of neurons that receive touch information in human fingers are very long because they have to reach from the spinal cord to the fingertips. The neurons in your ear, in contrast, have hairlike protrusions that move in response to sound vibrations. The neurons that sense pressure on your skin are buried deep; those that sense pain spread fine spidery endings very close to the surface.

The external surface of some cells can be studded with a huge variety of structures. Single-celled organisms in particular may be covered with cilia or other tiny hairlike structures, plates of mineral or organic armor, or sheaths of gelatinous ooze, which are manufactured by the cell itself. Most cells bear thousands of different receptors that enable signaling chemicals such as hormones to react with cells, and others that allow cells to interact with one another. Cells also have channels and transport proteins that allow some molecules to cross the membrane but keep others either in or out.

In multicellular organisms, cells are often surrounded by an extracellular matrix (ECM), a web of material that holds cells in place and stores materials for later use. The ECM is especially important during development, because it provides a pathway along which cells locate their destinations. The ECM degenerates with age, leading to less elastic, sagging tissue.

▼ PLASMA MEMBRANE

All cells are surrounded by a plasma membrane, which allows some molecules to pass into and out of the cell but denies access to others. The plasma membrane is thought to consist of two layers of phospholipid molecules with globular proteins embedded among them, arranged in a random mosaic pattern.



CLOSE-UP

The passage of molecules

Cell membranes select which molecules are allowed to move into and out of cells by using specialized pores called channels, or proteins called receptors. Channels allow only certain molecules, like sodium or potassium ions, across the membrane. Channels can be gated, so that molecules are allowed through only under certain conditions, such as when electrical charges change or particular hormones interact with the cell. Receptor and transporter proteins sit on or in the membrane, ready to bind a particular kind of molecule, known as the substrate. The substrate fits the receptor protein like a key in a lock. When a substrate binds its receptor, the receptor signals the inside of the cell to respond or to bring the substrate inside the cell. Transporter proteins are like receptors, but receptors only bind molecules whereas transporters move molecules across the membrane into or out of the cell.

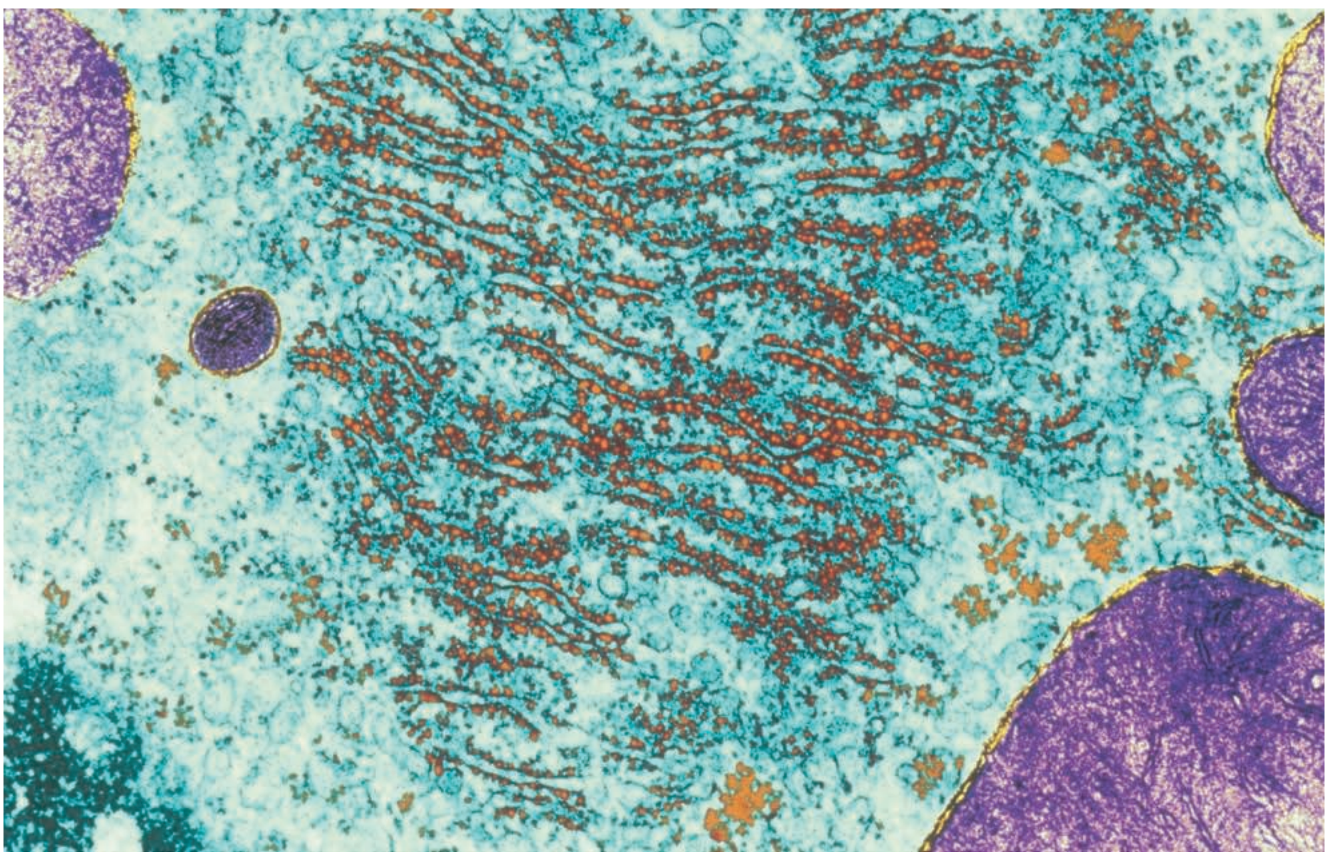
Cell internal anatomy

Eukaryotes, including plants, animals, and fungi, have a cell membrane, and plants and fungi also have a cell wall. One of the main differences between prokaryote and eukaryote cells is that chemical reactions in the latter are often contained within small compartments, called organelles, or "little organs." Examples of organelles include mitochondria (singular, mitochondrion), which harness energy from food; and nuclei (singular, nucleus), which hold genetic information and control how this information is used. Other organelles include lysosomes, endoplasmic reticulum, and the Golgi apparatus, all of which are essential for the construction of proteins. The first appearance of organelles marked another major step in the evolution of life. The "endosymbiont" theory proposes that eukaryote cells first formed when one prokaryote cell engulfed another. Instead of being digested as food, the engulfed cell continued living within the host, for which some of its functions served a useful purpose. Thus the engulfed cell began acting as an organelle. The fact that mitochondria are enclosed by a double membrane and contain their own DNA supports the idea that they have evolved from independent cells.

The work of cells

One of the most important jobs of a cell is to manufacture proteins. Many proteins are made as part of routine maintenance, just to keep the cell alive and healthy, but others are made in response to some outside influence. For example, when an animal like a dog or human eats, its digestive system breaks down the food into basic component molecules, which can be taken up by intestine cells and then transported all over the body. One of the most important of these is the sugar glucose. Receptors in an

▼ **CELL STRUCTURES** *This electron microscope image of a cell shows several internal structures. The curved strands are the rough endoplasmic reticulum, the dots on these curves are ribosomes, and the large purple structures are mitochondria.*



CONNECTIONS

COMPARE the genetic material of a eukaryotic cell with that of prokaryotic cells such as ***BACTERIA***. In the eukaryotic cell, the DNA is arranged within a nucleus, but a prokaryotic cell does not have a distinct nucleus.

organ called the pancreas detect increased levels of glucose in the circulation and trigger its cells to manufacture and release a protein called insulin. Insulin is a hormone. Having been released into the blood, it is carried around the body, binding to specialized receptors on many other cells and encouraging them to take up glucose using a protein called a glucose transporter. Glucose can then be used as an energy source for all of the cell's functions. This may seem like a simple pathway, but it is actually a complex set of steps involving all parts of the cell.

Nucleus

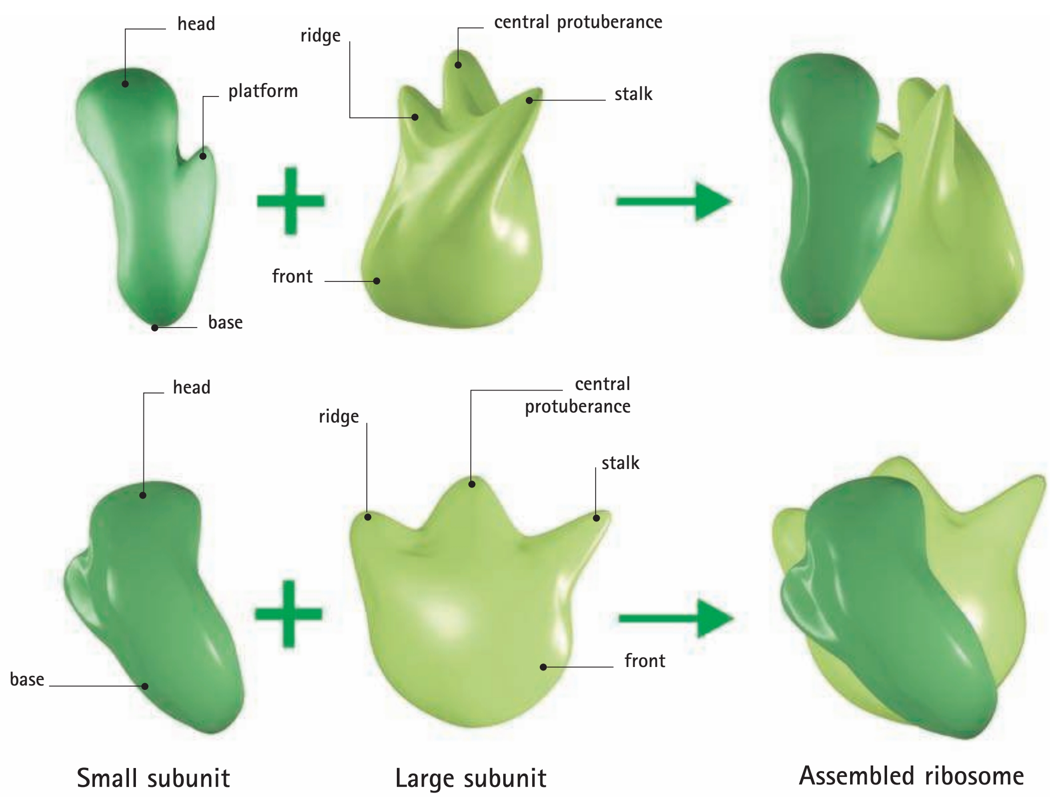
Cell nuclei are the storage sites for chromosomes in all eukaryotic cells. The gene needed to make insulin, for example, is stored in the nucleus of every cell in the animal's body, but it is active only in those differentiated into pancreas cells. The nucleus has a membrane envelope that protects the chromosomes from damage and controls which genes are used to make proteins. Molecules called messenger RNAs (mRNAs) are made from the genes coded on particular strands of DNA.

Ribosomes

Ribosomes are tiny granular particles that assemble proteins. There are vast numbers of ribosomes in a cell. Ribosomes read mRNA transported out of the nucleus and use it as a template for building the specific protein required, for example, insulin. Some ribosomes are free-floating in cells. The proteins they make will also be free-floating in the cytoplasm. Other ribosomes are attached to a large network of membranes called the endoplasmic reticulum (ER).

Endoplasmic reticulum

ER that is covered with ribosomes is called rough endoplasmic reticulum. The ribosomes use mRNAs to manufacture proteins that will be built into membranes or packaged for storage or export in little bubbles called vesicles. When a cell needs a new membrane protein, such as a receptor in the cell membrane, the nuclear membrane, or the membrane of any other organelle, its ribosomes will weave the protein back and forth in the ER membrane as they assemble it. Small pieces of ER containing the new protein can be broken off, transported to other locations in



▶ BACTERIAL RIBOSOME
Electron microscopes have been used to discover the position of many proteins in the structure of a bacterial ribosome. The ribosome is made of two subunits that together use a form of RNA called messenger RNA to assemble proteins. This illustration shows the subunits, and the way they interlock, from two different angles.

the cell, and patched into the membrane where they are needed. When a protein is to be released outside the cell, rather than weaving the new protein into the membrane, the ribosome pushes it into the ER cavity, or lumen. Then small, bubblelike vesicles filled with the protein are budded off the main ER and can be moved to other parts of the cell. If the protein is to be exported, the vesicle moves to the cell membrane and fuses with it, expelling the contents outside the cell.

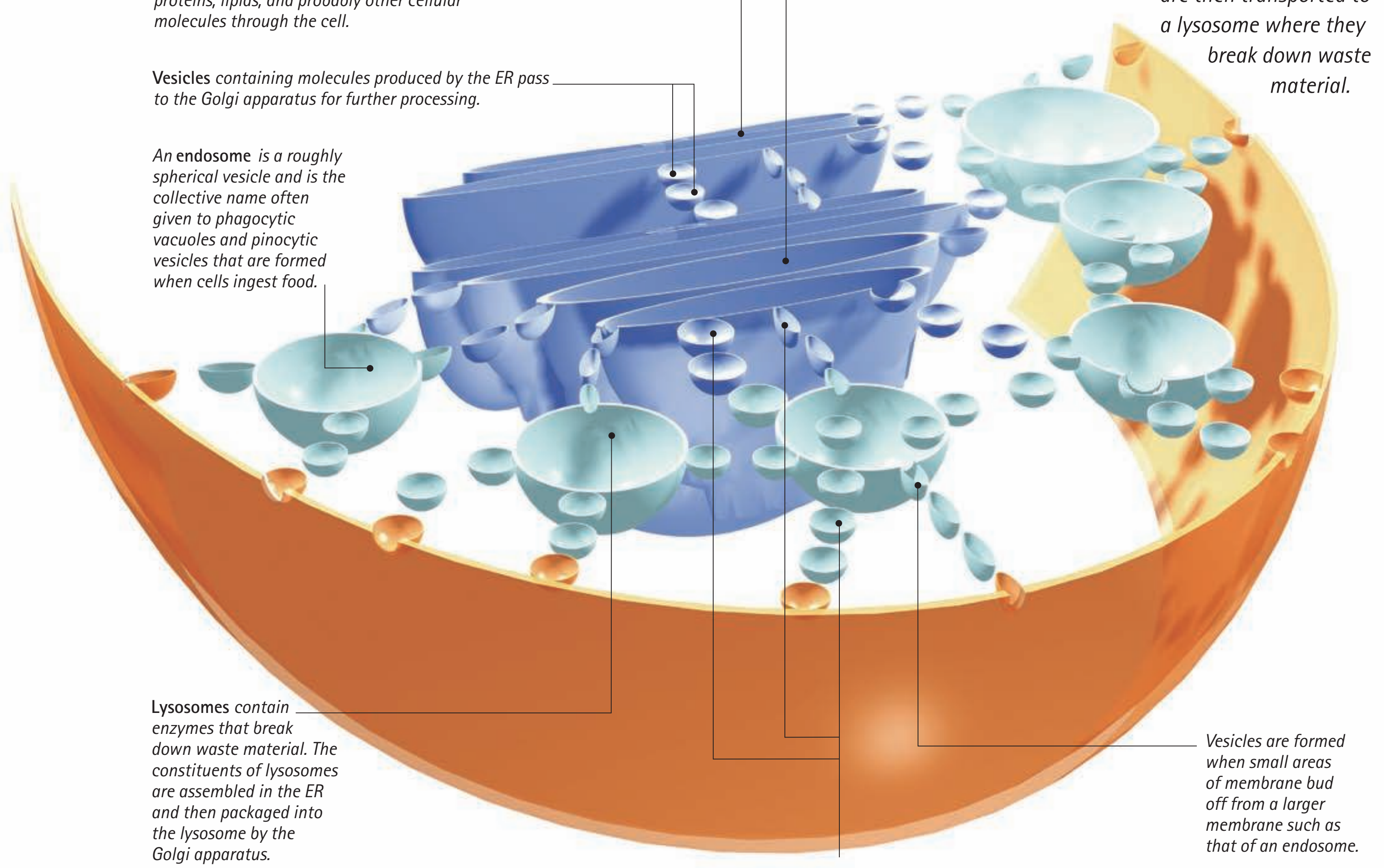
ER that does not contain ribosomes is known as smooth endoplasmic reticulum (SER). SER is involved in synthesizing steroid hormones like estrogen and testosterone and also helps detoxify drugs and other poisons.

Golgi apparatus

Most proteins synthesized on the ER need some kind of further processing before they can be useful. All this processing occurs in a structure called the Golgi apparatus, which looks like a stack of pancakes. The Golgi has two sides: cis, where proteins are received from the ER; and trans, from which processed proteins are dispatched to other parts of the cell. Proteins passing through the Golgi are trimmed to their correct size, assembled into groups, folded into intricate shapes, and decorated with sugars. These sugars have many functions—they help the protein fold correctly and allow it to be recognized by other cells, organelles, or molecules, for example.

▼ **GOLGI APPARATUS AND ENDOPLASMIC RETICULUM**

These two membranous organelles are involved in the production of many molecules necessary for the functioning of the cell. The manufacture of lysosomal proteins, for example, begins in the endoplasmic reticulum with the production of proteins with mannose sugars. The proteins then pass to the Golgi apparatus where phosphates are added, thus forming lysosomal proteins. The proteins are then transported to a lysosome where they break down waste material.



IN FOCUS

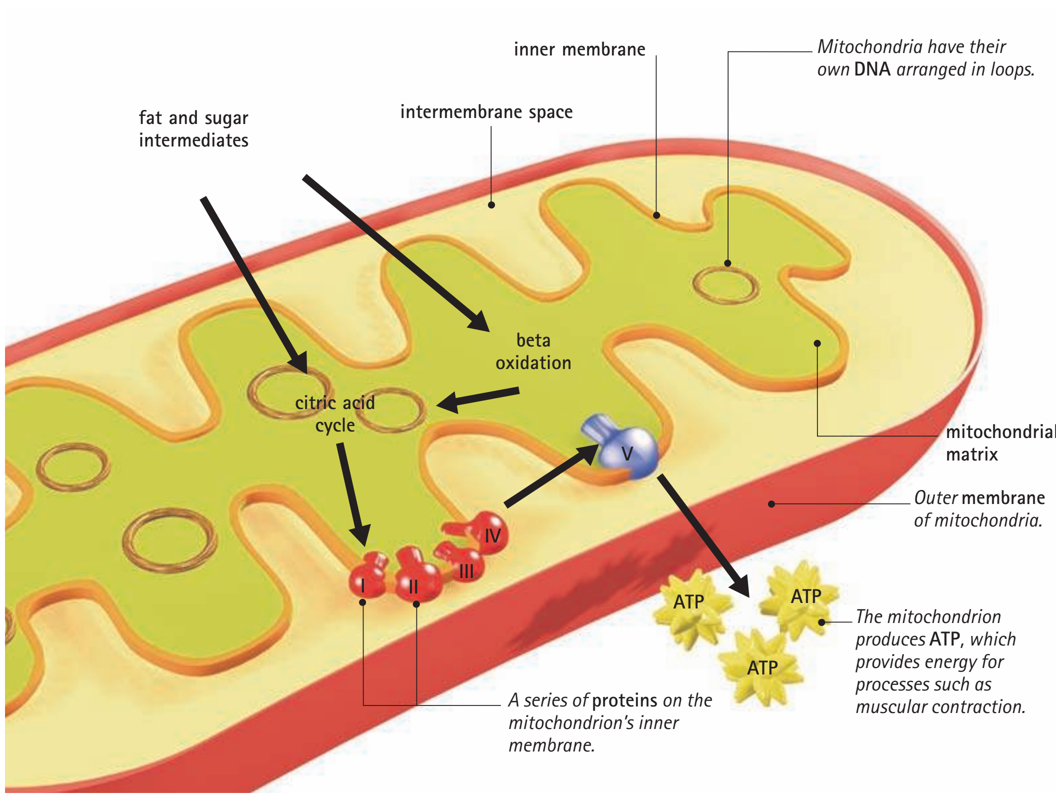
Helpful chemicals: Vitamins and antioxidants

Vitamins are molecules that perform vital functions in the normal activity of cells, smoothing and enhancing various metabolic reactions. Vitamins B and C, for example, are needed to make cofactors, molecules that activate various enzymes. Vitamin A is converted into retinal, a molecule that helps nerve cells in the eye detect light. Different organisms are capable of synthesizing different vitamins, but often there are others that have to be taken in ready-made as part of the diet. Most animals can manufacture their own vitamin C, but primates, including humans, can get it only from their food; that is why fruit is an important part of the human diet. Vitamin deficiencies can lead to severe problems.

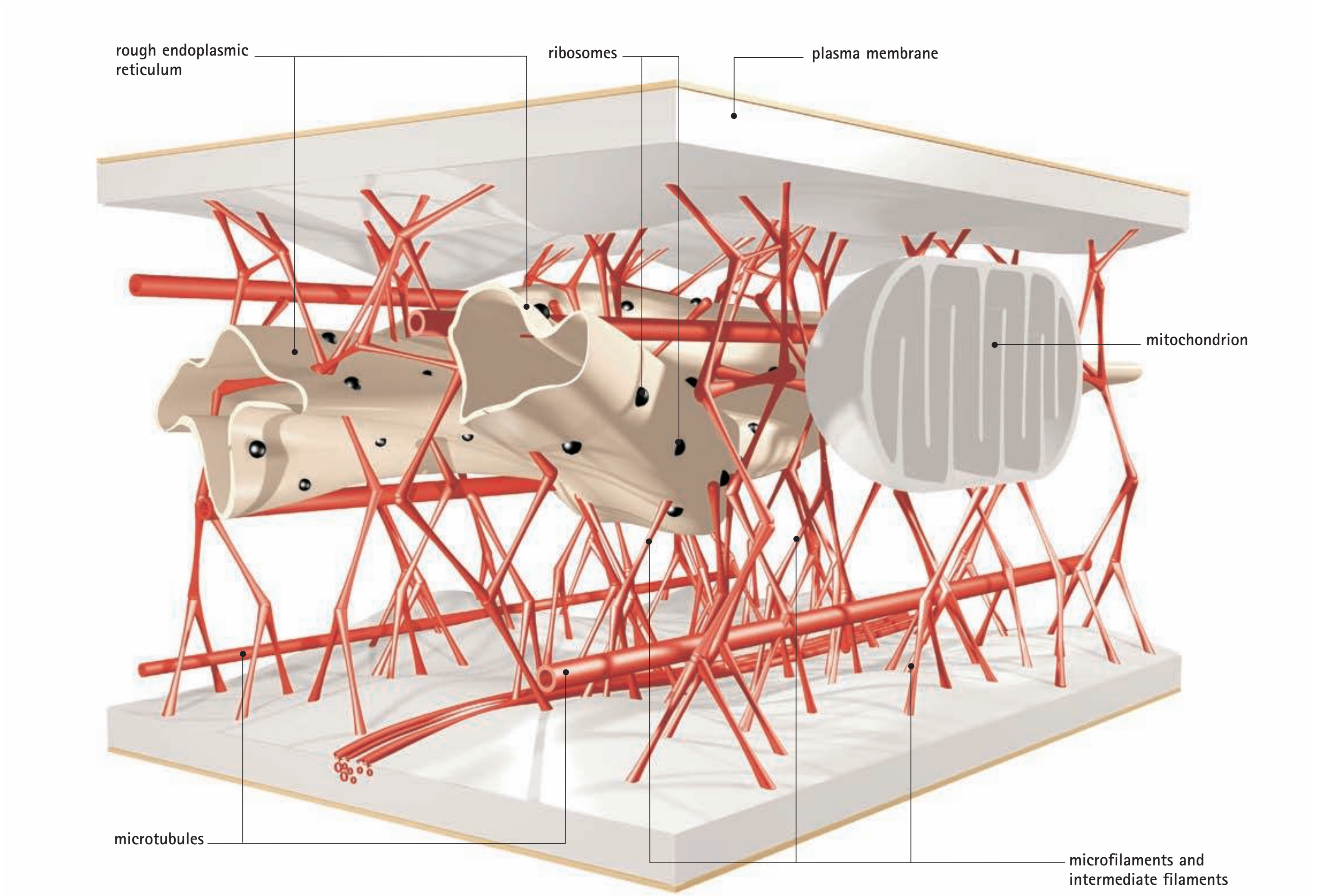
Many cell processes involve the movement of electrons from one molecule to another. Molecules that have lost electrons are said to be oxidized. Oxidation generates reactive molecules called free radicals, which can harm cells by damaging DNA and other important molecules. Free radicals contribute to the effects of aging, and play a role in health problems as diverse as heart disease, types of cancer, arthritis, and Alzheimer's disease. Antioxidants are chemicals that normally neutralize free radicals. Many vitamins, including vitamins C and E, are important antioxidants. The plant pigment beta-carotene, found in tomatoes and carrots, is another.

Mitochondria

Almost every process in the cell, from sending signals to making proteins, requires energy. Mitochondria (singular, mitochondrion) are the organelles that harness the energy from glucose and convert it into a form that can be used by other parts of the cell. Once glucose has been transported into the cell, it is quickly converted to a related molecule called pyruvate, or pyruvic acid, which cannot easily move back out of the cell. Pyruvate is then broken down in the mitochondria. Pyruvate is used to manufacture a chemical called adenosine triphosphate (ATP). ATP is the universal energy storage molecule and can be used by all organisms to sustain life.



▶ **MITOCHONDRION**
Mitochondria use fats and sugars in a complex series of chemical reactions to create a molecule called adenosine triphosphate (ATP), which is used as an energy store. Fats and sugars enter the mitochondrion and undergo processes called beta oxidation and the citric acid cycle. Protein complexes (labeled I to V) on the inner membrane together perform a further series of processes collectively called the electron transport chain. This results in the production of ATP, which is released into the cytoplasm of the cell.



A mitochondrion is surrounded by two layers of membranes, which create two separate compartments. Pyruvate is broken down in the innermost compartment of the mitochondrion, inside the inner membrane. Then several negatively charged particles (electrons) are extracted from it. This process releases energy to pump positively charged particles (protons), from between the two mitochondrial membranes to the innermost compartment. The protons then flow back between the two layers, providing energy to generate ATP. This whole process, which requires glucose and oxygen, is called cellular respiration.

Lysosomes and peroxisomes

Making proteins and using energy generate waste. Lysosomes and peroxisomes are structures inside the cell that use lysosomal protein produced in the endoplasmic reticulum and Golgi apparatus to gather waste, break it down, and neutralize potentially damaging molecules, such as hydrogen peroxide. The neutralized waste can then be eliminated from the cell through a process called exocytosis.

Cytoplasm and cytosol

All cell parts are suspended in a watery medium called cytosol, which bathes the organelles and helps the cell maintain its shape. Cytoplasm is made up of the cytosol and all the other cell contents, including organelles. In order for all cell processes to function properly it is essential that the cytoplasm contains the right mixture of chemicals to create optimum acidity (pH) and salt, glucose, and water content. Chemical reactions in the cytoplasm also affect the temperature of a cell.

▲ **CYTOSKELETON**
The cytoskeleton is a network of protein microfilaments, microtubules, and intermediate filaments that extends throughout the cell's cytoplasm. The cytoskeleton provides structure for the cell and its organelles and is involved in cell movement.