# CENTRAL CONCEPTS OF BIOLOGY

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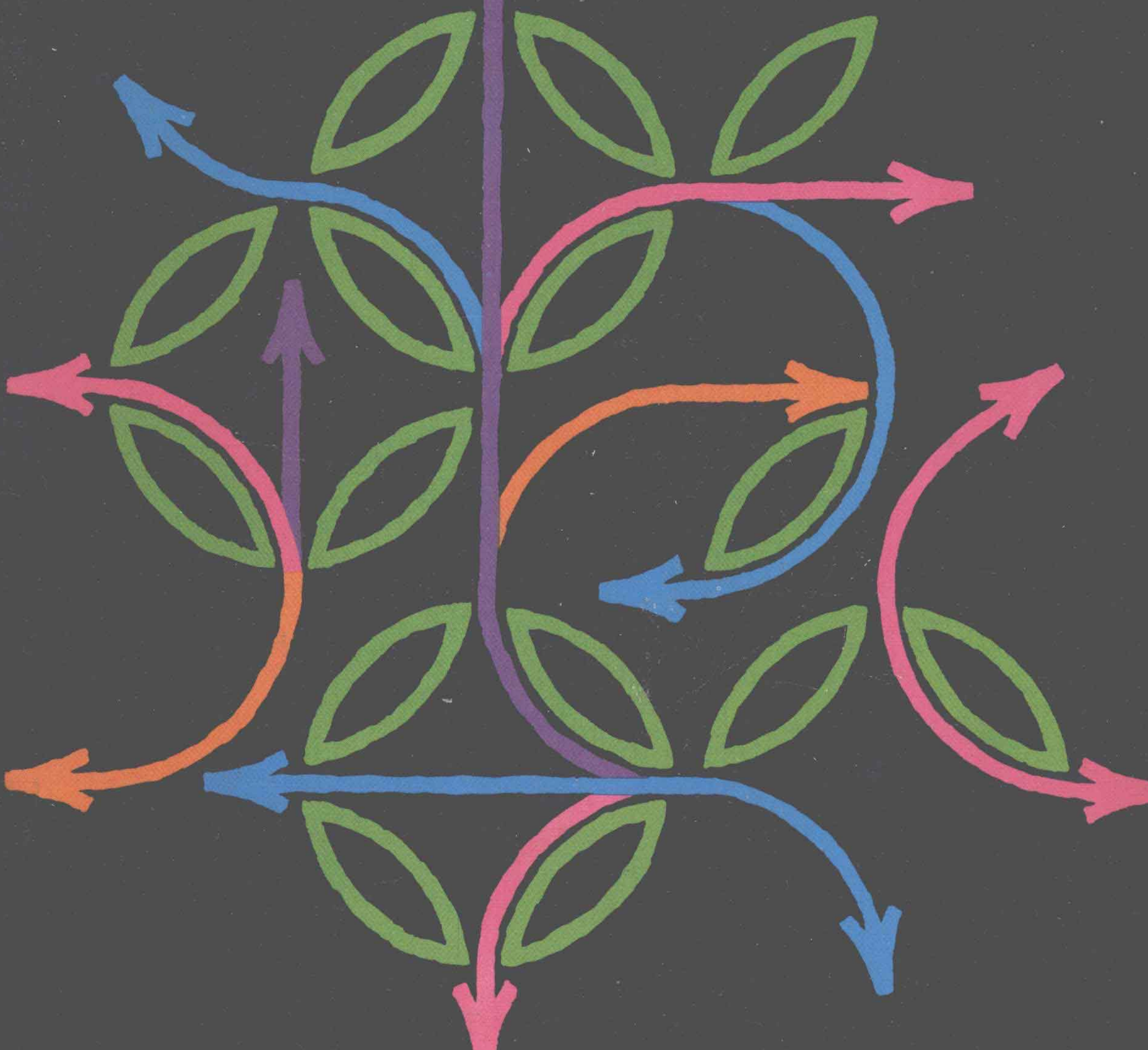

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# Preface

THIS book is designed to introduce the reader to biology by examining a selection of fundamental concepts in this science. It is introductory in the sense that no extensive knowledge of biology is presumed. It is general in that it selects and synthesizes data from the various areas of biology and devotes some attention to the interdependence of fact and theory. It is, however, also highly specific; that is, a few concepts are considered in detail, with supporting observations and experiments.

To meet these objectives, areas of biology have been chosen for discussion because of their logical internal development and their interrelations. In the study of physiology we consider the organization and function of biological structure and show their relation to chemical processes (metabolism) and to energy acquisition and use (energetics). In genetics we consider the reproduction of life forms and their inherent diversity. In ecology we consider populations in relation to the physical environment and to one another. And in evolution we consider the long-term adaptive forces at work on populations in their natural setting. Other biological subject matter, of no less intrinsic interest, has been excluded from this book or only briefly discussed in it. For example, the classification of organisms into groups on the basis of structural relationships (taxonomy) and the physiology and anatomy of special groups of organisms seem to us best left to the laboratory or field, where the particular choice of what to study is determined by the organisms locally available. On the other hand, we present information from disciplines outside biology when it is needed to substantiate biological theories. We assume that the reader has had a course in general science and has a knowledge of algebra.

We have attempted to develop the subject matter logically, in contrast to other possible ways of treating this material, such as historically or in an encyclopedic fashion. Thus in ecology, we describe the relationship of measurable characteristics of a population, such as rate of growth, to theories of competition and predation. Exploration of these aspects of ecology is made possible by the development of the concepts of energetics in the earlier section on physiology. But such ecological subjects as the succession of communities and a description of the various types of vegetation have been entirely omitted for the sake of brevity, in spite of their importance in understanding the past and present associations of life forms on earth. The section on ecology serves a second function: it facilitates the discussion of evolution by showing how selection pressures on populations might operate concretely in terms of birth and death rates. As these considerations indicate, the four branches of biology discussed in the book are interdependent. Together they illuminate the unity of biology as a science.

PREFACE

We have chosen to present original data in this book whenever possible because we think that this practice allows the reader to perceive the world of biologists most vividly. Citations of these original data are in the references at the end of the chapters. The legends of the figures contain credits for the sources of illustrations and full citations are usually listed among the references. Additional suggested reading is also listed at the end of chapters.

Numerous friends, colleagues, and students have offered valuable suggestions on our manuscript. We thank all of them for their help. At the same time, we accept final responsibility for the book. We would appreciate being informed of errors that occur in it.

We are grateful to Miss Chris Benson, Mr. Dan Rondeau, and Mrs. Fran Whitfield for typing the manuscript and for other clerical assistance.

A. S. B.
W. E. H.
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W. C. S.

# Contents

# 1

# Introduction

THE fundamental concepts that underlie all biological disciplines are those which transcend taxonomic categories of life forms and are thus generally applicable. From our perspective the concepts of crucial importance are

1. The common features of cellular and subcellular structure.
2. The ubiquitous nature of mechanisms to extract energy from the environment.
3. The common nature of synthetic and degradative biochemical pathways.
4. The common nature of the genetic material and genetic mechanisms.
5. The universality of the struggle for survival and reproduction.
6. The change in life forms through space and time.

This book is built upon these six concepts, and examples are drawn from diverse organisms in illustrating them. Through the application of these concepts many, but not all, biological problems can be brought into focus and substantially understood. However, the solving of biological problems requires some familiarity with appropriate methods of investigation, in addition to a reasonable conceptual framework. To a large extent, methodology and conceptual framework are interdependent.

The principal value of these six concepts is that they call attention to the high degree of order which is repeated in biological systems at different levels, order which is a manifestation of the universal ability of living organisms to maintain themselves in an improbable, nonrandom state.

## Hierarchies of Biological Systems

There are a number of ways of viewing the orderliness of biological systems. First and most important, biological systems have orderly structures. Second, and intimately related to this, they have orderly functions. Although the general organization of biological functions is understood, some aspects of functional organization in time are still perplexing. To take a specific case, we still lack a comprehensive theory of the process of development in plants and animals, even though the development of the chicken and its implications for a theory of growth processes were discussed by Aristotle in the fourth century B.C.

We know that structural order in any life form is based to a large extent on the precise architecture of its component molecules. But organisms are not heaps of molecules; their molecules are aggregated into specific and dynamic clusters, films, fibers, sacs, and the like. These distinctive structures, collectively called organelles, have by now in most cases been painstakingly analyzed as to their molecular composition, molecular construction, and particular functions. But examining these bits and pieces of life provides us with only glimpses of its compass and splendor. For one thing, collections of organelles are elaborately arranged in superstructures which we call cells. Cells are functional organizations of organelles and fluids arranged in ways so subtle that it may be a long time before they are thoroughly understood.

But not all cells are alike in their structure. Although the cells of most familiar organisms are made up of organelles, the cells of some inconspicuous life forms are not. For example, the microscopic bacteria so plentiful in soil, still water, and animal intestines are individual cells with a membranous film surrounding them and little else in the way of distinct structure. At the same time, bacteria do contain the basic types of molecules characteristic of life forms and they do function well. How these molecules are organized inside bacterial cells is just now being explored.

In striking contrast, the cells of "large" organisms are replete with organelles. Large plants range from mushrooms and seaweeds through mosses and olive trees, and large animals from sponges through earthworms, moths, and mammals. Notably, many of the organisms larger than bacteria, whether plant or animal, are multicellular; some, such as the pond-living paramecium, are unicellular. Virtually all the cells in multicellular forms are arranged in discrete functional groups called tissues. Some of the tissues of human beings are muscle, blood, and the epithelial tissue which covers all free surfaces, such as the skin. Furthermore, just as cells consist of a definite assortment of different organelles, tissues consist of a definite assortment of different cells, each type having its own structural and functional idiosyncracy.

Tissues, in turn, are arranged harmoniously into organs. The reliability of the heart is embodied in its tissues: its muscular walls, its delicate nerve endings, and that cell-laden stream, the blood.

This hierarchy of molecules, organelles, cells, tissues, and organs—including their myriad ramifications and intertwinings—defines in an analytical sense the improbable organization of a petunia, a penguin, you, or even, despite the generation gap, your parents.

Just as significant, each orderly individual organism is an intrinsic part of higher levels of biological organization—of a population and a species, on the one hand, and of an ecosystem on the other. These are not discrete entities like organisms, and the degree of reality assigned to them depends on the outlook of the individual studying them.

Individuals that are capable of reproducing with each other, or at least with those of a different sex, conjointly make up a species. Members of a species usually look similar and usually live in geographical proximity. But not necessarily. A species may have several populations, only tenuously connected geographically. Not only are individuals in the same population capable of breeding together, their proximity ensures that they usually do (if they live to maturity and are not sterile).

Of equal interest is the fact that individuals in a given population may live in the same habitat, like bees in a hive, or may live dispersed, like bears in a hill country. The habitats of individuals in a population may be as alike as two monks' chambers or as different as a berry bramble and a hole in a tree. But all these habitats and their occupants may be part of the same ecosystem. Bees feed off the nectar and pollen of flowers, including those of berry bushes, and both their young and their honey are sometimes confiscated from a knot hole and eaten by bears—who also feed on blackberries when they can. People too have a penchant for honey and berries, and if they are intrepid enough, even for bear meat.

An ecosystem, then, is a community of diverse plants and animal species, in competition for food and other resources and often forming a series of food supplies, the species at one level in the series being the sustenance of those at the next level. By such interactions the biological world maintains itself as an orderly system in space.

Its orderliness in time is even more notable, as is witnessed by the venerable span of life on earth—several billion years. The evident changes in species during this enormous time—that is, their evolution—are a triumph of orderly biological responses to changes in the environment of the planet. Order in time is likewise seen in the development of a chicken from an egg, or of an oak from an acorn. Faced with this microcosm of order in a macrocosm of physical laws favoring disorder, the universe, as Alice said in Wonderland, gets curiouser and curiouser.

## Hierarchies of Biological Classifications

Not only can the levels of biological systems be arranged in a hierarchy, but the organisms themselves can also be arranged in ranks. A number of different systematic schemes have been proposed for plants and animals; the most familiar scheme places all the plants in one "kingdom," all the animals in another. Some of these systematic schemes introduce a third kingdom, the protists, which includes bacteria, blue-green algae, the one-celled organisms with flagella (whip-like structures), the protozoa such as *Amoeba* and paramecium, and the slime molds. No taxonomic scheme is completely satisfactory; as a corollary, no scheme has been accepted universally.

Different kinds of organisms are distinguished on the basis of their differences in structure, function, and developmental history. A biologist hopes that the evolutionary history of organisms deduced from these specializations will be reflected in the hierarchy of taxonomic ranks in a classification scheme. If a number of kinds of organisms are alike in specializations, that group may be assigned a taxonomic rank. All those animals having the specialized structures of hair and mammary glands are assigned to the mammals; all plants reproducing by flowers are assigned to the angiosperms. Within the larger groups there are

**Table 1-1**
**Classification of organisms**

**Kingdom Protista**

Phylum Schizophyta—bacteria: *Escherichia coli, Hemophilus, Bacillus*
Phylum Cyanophyta—blue-green algae
Phylum Flagellata—one-celled flagellates, including some algal forms
Phylum Sarcodina—*Amoeba*
Phylum Sporozoa—*Plasmodium*
Phylum Ciliophora—ciliates: *Paramoecium, Didinium*
Phylum Myxomycetes—slime molds: *Physarum*

**Kingdom Plantae**

Phylum Chlorophyta—green algae
  (Related phyla contain other algae: yellow, brown, red.)
Phylum Mycophyta—fungi: *Neurospora* and other molds, yeast, blights, mushrooms
Phylum Bryophyta—mosses, liverworts
Phylum Tracheophyta—vascular plants
  Subphylum Pteropsida—ferns and seed plants
    Class Gymnospermae—conifers, such as pines, firs
    Class Angiospermae—seed plants
      Dicots—peas, *Delphinium, Mimulus*
      Monocots—grasses, corn, onion

**Kingdom Animalia**

Phylum Porifera—sponges
Phylum Coelenterata—*Hydra,* jelly fish
Phylum Platyhelminthes—*Planaria,* flukes, tapeworms
Phylum Aschelminthes—rotifers, round worms
Phylum Mollusca—mollusks, including the snail *Cepaea,* and squids
Phylum Annelida—segmented worms
Phylum Arthropoda
    Class Crustacea—copepods, *Daphnia,* barnacles, lobsters, shrimp
    Class Arachnida—spiders, mites, ticks, scorpions
    Class Insecta—insects: cockroaches, grasshoppers, moths, butterflies, sawflies, true flies, mosquitos, beetles, ants, bees, wasps
Phylum Echinodermata—sea urchins, starfish
Phylum Chordata
  Subphylum Vertebrata
    Class Chrondrichthyes—sharks
    Class Osteichthyes—bony fish
    Class Amphibia—frogs, toads, salamanders
    Class Reptilia—snakes, lizards, crocodiles, turtles
    Class Aves—birds
    Class Mammalia—kangaroos, mice, gophers, foxes, antelopes

smaller groups with finer differences, and these are given lower ranks. The formal taxonomic ranks are phylum, class, order, family, genus, and species. In the Class Mammalia, those animals with certain common specializations of the teeth for eating insects are assigned to the Order Insectivora, including moles and shrews; others with different specialized teeth are assigned to the gnawing mammals, the Order Rodentia. Added to the formal taxonomic ranks are informal groupings such as the invertebrates, comprising all animals without backbones.

The classification given in Table 1–1 is fragmentary; no attempt is made to integrate the viruses into this system or to list all the phyla of the kingdoms, some being of interest only to specialists. Organisms listed as examples of different taxonomic groups are those discussed in this book or those that are generally well known. The complete classification of three disparate species, given in Table 1–2, indicates the wealth of specialized adaptations to nature available in the living world.

**TABLE 1–2**
**Classification of three organisms**

| | Pea plant | Laboratory fruit fly | Man |
|---|---|---|---|
| **Phylum** | Tracheophyta: plants with specialized conducting tissues | Arthropoda: animals with an external skeleton and jointed appendages | Chordata: animals with a stiff dorsal rod |
| **Class** | Angiospermae: flowering plants producing fruits with seeds inside | Insecta: body divided into head, thorax, abdomen; 1 pair of antennae | Mammalia: with hair and milk glands |
| **Order** | Leguminales: trees, shrubs, herbs with fruit-like pods | Diptera: 1 pair of wings, development with a larval stage | Primates: with fingers and flat nails |
| **Family** | Leguminosae: 5 petals, 2 often fused, 10 stamens | Drosophilidae: small flies, larvae often in decaying fruit | Hominidae: upright posture, flat face |
| **Genus** | *Pisum*, pea plants | *Drosophila* | *Homo* |
| **Species** | *Pisum sativum*, garden pea | *Drosophila melanogaster* | *Homo sapiens* |

# 2

# Major Features of Cells

OVER 300 years ago the term "cell" was applied to the compartments seen inside plant tissues. But the recognition that cells are the basic units of all living structure is only slightly over 100 years old. With this recognition came the belief by many biologists that life could best be understood by investigating the structure and function of these fundamental units of organisms. We know now that interactions between cells result in properties which one cannot necessarily predict from the behavior of single cells, and that these interactions determine much of the behavior of multicellular systems. Even so, an understanding of the parts is a useful prelude to an understanding of the whole. With this rationale we begin our inquiry into the properties of biological systems by considering in a general way the structure and function of cells.

## General Characteristics of Cells

Cells are the smallest biological systems that have the machinery necessary for day-to-day maintenance and for the production of more units like themselves. Of course they rely on their surroundings for raw materials to carry out these life processes.

Although some cells are visible to the naked eye, most are microscopic in size. To observe even the grossest features of cells, then, they must be made to appear larger. Until recently, the only means of accomplishing this was by the use of the light microscope, which consists of a set of magnifying lenses placed between the eye and the object to be viewed. In the compound light microscope, light is passed through the object and is then directed into a multiple lens system. A magnified image of the object comes to a focus in space just above the last series of lenses and is cast onto the retina of the eye. Often a camera is substituted for the eye and the resulting picture of the object can be enlarged any desired number of times. Unfortunately, however, magnification alone is not enough if one is to see details of cells clearly. If a small fuzzy picture is magnified, the result is a large fuzzy picture. Magnification, to be effective, must be accompanied by increased resolution. Resolution is the ability to perceive separate structures as being distinct from one another. Good resolving ability is indispensable if an optical system is to produce clarity of detail.

The major factor limiting resolution is the wavelength of light used in forming the image of an object. That is, the shorter the wavelength used, the greater the possible resolution. Since the wavelength of visible light is about 0.5 $\mu$ (see Fig. 2–1 for metric equivalents), a light microscope can only resolve objects which are approximately this far apart or farther.

| Limits of Resolution | SIZE | | | | Atoms and Molecules | Cells | Organisms |
|---|---|---|---|---|---|---|---|
| | Angstroms | Microns | Millimeters | Meters | | | |
| | 1 | | | | Hydrogen (H) | | |
| Electron microscope | 10 | | | | Amino acids | | |
| | 100 | | | | Proteins | | |
| | | | | | | | Viruses |
| Light | 1000 | | | | | | PPLO |
| microscope | 10000 | 1 | | | | | Bacteria |
| | | 10 | | | | Red blood cell | |
| Naked eye | | 100 | | | | Human egg | Paramecium |
| | | 1000 | 1 | | | | Drosophila |
| | | | 10 | | | | Mouse |
| | | | 100 | | | | |
| | | | 1000 | 1 | | | Man |
| | | | | 10 | | | Whale |
| | | | | 100 | | | Sequoia tree |

**Figure 2–1.** *Range of sizes from atoms to large organisms: 10000 Angstrom units (Å) equal one micron ($\mu$), 1000$\mu$ equal one millimeter (mm), and 1000 mm equal one meter (m). (Modified from* Heredity, Evolution, and Society, *by I. Michael Lerner. W. H. Freeman and Company. Copyright © 1968.*

### *Major Cellular Structures*

One can see a fair amount of detail in cells with the use of the light microscope (Fig. 2–2). Although particular cells of plant and animal tissues are somewhat different in appearance, their basic similarity is striking, despite the possession by plant cells of a cell wall and of bodies called plastids. All cells possess a cell membrane, or plasma membrane, which encloses the internal parts and which allows some materials to pass in and out but excludes others. Such a membrane is said to be selectively permeable. All plant and animal cells possess a large internal body called the nucleus (pl., nuclei), in which thread-like bodies called chromosomes can be seen at certain times. Chromosomes bear the inherited (genetic) information, the genes, which are ultimately responsible for directing the functions of cells. The nucleus is bounded by a membrane and the cytoplasm lies between the nuclear and plasma membranes.

Throughout the cytoplasm there are, characteristically, small membrane-bound bodies (organelles), which can be seen only indistinctly with light microscopy. Briefly, these organelles are mitochondria, which extract energy from foodstuffs

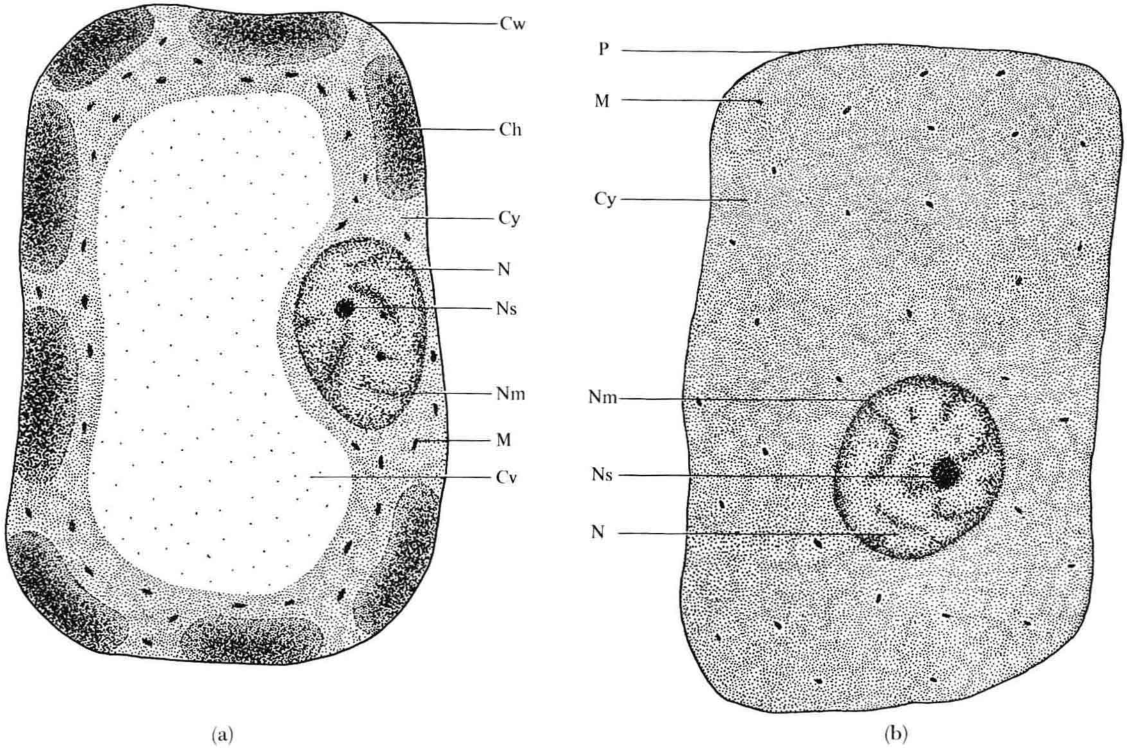



**Figure 2–2.** *(a) A plant cell from the leaf of* Syringa *and (b) an animal cell from a frog embryo. Cw, cell wall; Ch, chloroplast; P, plasma membrane; N, nucleus; Ns, nucleolus; Cy, cytoplasm; M, mitochondrion; Cv, central vacuole; Nm, nuclear membrane. (Drawn from prepared slides, courtesy of Bryan Burnett.)*

and convert it into a biologically useful form; plastids (for example, chloroplasts) in plant cells, which contain pigments for transforming the sun's radiant energy into the chemical energy of molecules such as sugars; the Golgi apparatus, a system of canals commonly seen in secretory cells; and lysosomes, which contain chemicals capable of digesting food particles and cellular substances.

With light microscopy, the cytoplasm in which these organelles lie appears to be homogeneous. Actually, however, it contains much fine structural organization (as revealed by other methods of observation), such as the endoplasmic reticulum, a membranous network of channels, which transports certain materials from place to place within the cell. On the outer surface of some of these tubular channels lie the ribosomes, very small nonmembranous bodies which take part in the synthesis of proteins. Such features, along with the methods of their observation, will be discussed in depth in Chapter 4.

### *Major Cellular Activities*

The overwhelming problem faced by cells and other biological systems is, rather obviously, survival. Survival requires not only maintenance of biological structure during the lifetime of an individual cell but, if the cell line is to continue, maintenance of specific biological structure from generation to generation. The remainder of this book is largely concerned with the solutions to these survival problems. For the present, and using cells as an example of biological systems, we shall examine the major means by which long- and short-term maintenance are achieved.

**LONG-TERM MAINTENANCE.** Cells reproduce by replicating their chromosomes and partitioning these structures equally into two offspring or daughter cells. The processes of cell reproduction, mitosis followed by cell division, are shown in Figure 2–3 as they occur in root tip cells of *Allium cepa*, an onion. Every species of animal and plant has a characteristic number of chromosomes, and for *A. cepa* this number is 16. For much of a cell's life, the chromosomes are indistinct, as viewed with light microscopy; this period is called interphase. Shortly before cell division, at the mitotic stage called prophase, the chromosomes become conspicuous, and each clearly consists of two parts. These parts are believed to be qualitatively and quantitatively equal, representing duplicate sets of genes.

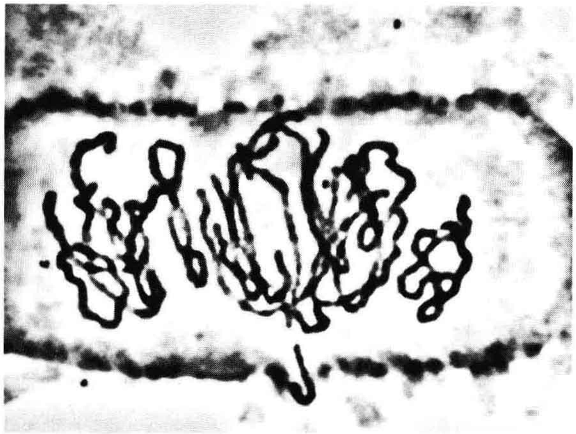
In late prophase, the nuclear membrane disappears, and each bipartite chromosome becomes associated with a group of fibers, the spindle fibers. Next, the chromosomes move, apparently guided by spindle fibers, to a central plane where they become precisely aligned; this is the metaphase stage. In anaphase, the two parts of a single chromosome (daughter chromatids) separate, and these, attached to spindle fibers, move away from one another. This culminates in the equal distribution of chromosomes to opposite poles of the cell. Each group of chromosomes is then enclosed by a new nuclear membrane and the chromosomes become indistinct; this is telophase. Cell division quickly follows, giving two cells with identical genetic information. Since chromosomes are unitary structures at their last appearance (telophase) and dual structures at their first (prophase), chromosomal replication evidently occurs during interphase.

The process of mitosis described above is fundamentally similar in all animals and most plants. Cells of these organisms are said to be eukaryotic: to have true nuclei. Bacteria and related types of organisms, however, have no distinct nucleus, and they partition their genetic information differently; they are prokaryotic. Cell division in prokaryotes will be considered in Chapter 11.

The events of mitosis have implications which are seemingly paradoxical. Multicellular organisms are derived from many mitotic divisions of a single cell. If mitosis results in partitioning of identical genetic information to daughter cells, and if this information determines how cells are built and how they function, why are not all cells in a multicellular organism identical? They obviously are not, and the reasons for this will be explored later in this book.

**SHORT-TERM MAINTENANCE.** Cells are dynamic rather than static systems. That is, most cellular components are not analogous to bricks in a building which, once in place, remain indefinitely. Instead, the molecules out of which cells are built are constantly being degraded and replaced. This was first shown by Schoenheimer and his co-workers in the 1930's.

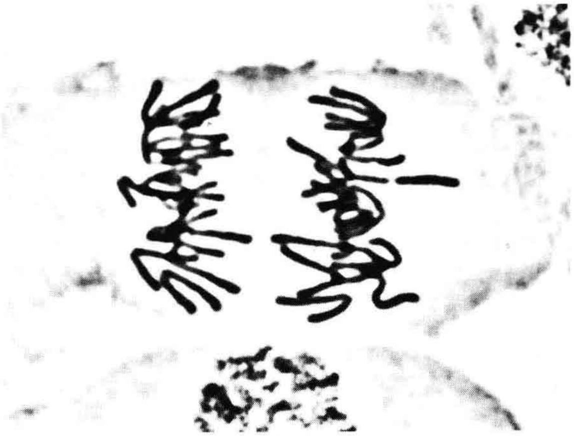
Schoenheimer (1942) took advantage of the fact that certain elements consist of atoms that have different weights. Most hydrogen atoms, for example, are



(a)

(b)

(c)



(d)

(e)

**Figure 2-3.** *Mitosis in root tip cells of* Allium cepa. *(a) Prophase: the chromosomes are distinct, the nuclear membrane has disappeared. (b) Late prophase: the chromosomes, guided by spindle fibers, are moving to a central plane. (c) Metaphase: the chromosomes are aligned on a central plane; each chromosome is clearly double. (d) Anaphase: the chromosomes have split and the daughter chromatids are moving to opposite poles. (e) Telophase: the chromosomes have reached opposite poles and are becoming less distinct. (Courtesy of Marilyn Corodemas.)*

identically light in weight, but a certain percentage are measurably heavier; one of these heavy types is called deuterium. Similarly, a small percentage of heavy nitrogen atoms exists in company with the standard lighter type. For his experiments, Schoenheimer incorporated heavy hydrogen into the structure of dietary fat molecules, out of which cells can synthesize storage fat, and heavy nitrogen into molecules of dietary amino acids, out of which cells can make proteins. Proteins are very large molecules which contribute significantly to cellular structure. Adult rats were fed the "heavy" fats and heavy amino acids. Later, fats and proteins were extracted from the animals' tissues and found to contain significant amounts of heavy hydrogen and nitrogen. Since the rats were fully grown and were maintaining a constant weight, the heavy fat and protein must have *replaced* existing fat and protein in their cells.

The rate at which body components are replaced varies considerably. For example, 50 percent of the protein-nitrogen in rat liver is replaced in as little as seven days. However, collagen, an extracellular protein found in cartilage, appears to be completely stable once formed. It is the only known body constituent that apparently is never replaced. All others are replaced at some measurable rate, although some, such as deoxyribonucleic acid (DNA), the genetic material, approach collagen in degree of stability. In any event, the phenomenon which Schoenheimer called the "dynamic state of body constituents" is now known to be a general and quantitatively important feature of most cellular components.

How is this requirement for replacement of parts met by cells? Obviously, cells must produce such components more or less continuously. This implies that cells must possess a whole set of abilities if they are to survive even for short periods. Some of these abilities, which account for the major activities of cells, are

1. **THE ABILITY TO ACQUIRE RAW MATERIALS FROM THE ENVIRONMENT.** While some required substances enter cells spontaneously by diffusion, others must be carried across the cell membrane by means of a different transport mechanism. All cells, then, must be capable of moving materials from the external medium to their interiors.
2. **THE ABILITY TO CARRY OUT SYNTHESES.** Once inside the cell, raw materials must be assembled into the large molecules out of which cells are made. The ability to synthesize such molecules is necessary both for growth and for replacement of parts.
3. **THE ABILITY TO ACQUIRE ENERGY.** In order to carry out transport and synthesis, both of which involve movement and therefore work, cells must have the ability to acquire energy. In all cells, this energy is derived from the step-by-step breakdown of energetic molecules such as sugars. Energy released in this way is "trapped" in other molecules, which then directly contribute to the work of transport and synthesis.
4. **THE ABILITY TO REGULATE CELLULAR ACTIVITIES.** In order to acquire energy and to use it efficiently in performing biological work, cells must regulate the rates at which various biological events occur. For example, a cell that is merely replacing its parts need not synthesize protein at the same rate as a cell which is growing rapidly. Cellular regulatory