Cells and Organisms

Chapter 1

Life Cells, and Organisms

Life is difficult to define, although there are characteristics that are used to separate the living and nonliving worlds. Several unifying themes exist in the living world. Despite the characteristics that all living organisms share, still much diversity exists. Biologists attempt to classify the hundreds of thousands of organisms using both traditional and novel approaches. The characteristics of life, along with the unifying themes, diversity, classification, and study of life are summarized in the Key Concepts at the end of the chapter.

- Although life is difficult to define, there are six key ingredients: genetic information (DNA or RNA); mechanism of energy production; machinery to make more living matter; an outward physical form; the ability to reproduce; and the ability to adapt.

Despite the lack of a satisfactory definition for life, all living organisms share criteria that include the use of nucleic acids, such as DNA or RNA as the form of inherited information. During reproduction, the genetic information is passed from parent to offspring.

In order to grow and reproduce, all living organisms much be able to extract energy from the environment, which is then used by ribosomes and other cellular machines to build more macromolecules.

All living organisms must adapt to changing environmental conditions, which is essential to evolution.

- Organisms are made of discrete subunits called cells.
  - Cells have a membrane layer that separates the inside portion or cytoplasm from the external environment.
  - Cells have enzymes in the cytoplasm that translate messenger RNA into proteins including enzymes.

All living organisms are made of cells. The simplest living organisms exist as single cells, whereas multicellular organisms consist of millions of cells, most of which are differentiated and have specific roles within the entire organism. For example, a human has hundreds of different cell types (red blood cells, nerve cells, epithelial cells), all of which not only look different, but have different jobs within the body.

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Not only are all organisms made of cells, but all cells come from pre-existing cells. Cells have a few features in common. As discussed in the first Key Concept, all cells contain nucleic acid as the form of inherited information. In addition to the nucleic acid requirement, all cells have a plasma membrane, comprised of lipids and proteins, that provides a barrier between the inside and outside environments.

Ribosomes are also a common feature among cells. These intracellular machines quickly translate the information stored in messenger RNA into proteins that have various roles within the cell.

The Three Domains of Life

- Prokaryotic cells have a cell wall, cytoplasmic membrane, soluble cytoplasmic enzymes, and a nucleoid region that holds a single chromosome.

The major difference between the two different cell types is the presence or absence of membrane-bound organelles, the largest of which is the nucleus. The simpler prokaryotic cells do not contain membrane-bound organelles, and consequently, do not compartmentalize their genomes away from the other subcellular components present in the cytoplasm, at least not within a membranous sac. Prokaryotes instead contain their genomes within the nucleoid region, which is not bound by a membrane.

- There are three domains of life: Eukarya, Eubacteria, and Archaea.

Biologists attempt to classify and order all life. Domains represent the highest, and broadest, level of biological classification. Even though they are different domains, Eubacteria and Archaea are prokaryotic, and thus have cell structures that do not include membrane-bound organelles and nuclei. Some of the differences between Eubacteria and Archaea will be discussed in a Key Concept below. The third domain, Eukarya, have cell structures that include membrane-bound organelles.

- Eubacteria are the most familiar prokaryotes since the members of this domain tend to cause human diseases.

The domain Eubacteria includes those prokaryotes that are commonly found on the human body and in yogurt or other foods. Unfortunately, Eubacteria often receive negative media attention because many are pathogenic, or disease-causing.

- Archaea and Eubacteria are both considered prokaryotes since they lack a nucleus surrounding their chromosome(s). Other cellular components of Archaea, including the cell wall, enzymes that synthesize proteins, and metabolic enzymes, are very different from Eubacteria, and in some cases resemble those of eukaryotes.

Even though both Archaea and Eubacteria are prokaryotic, they have many differences. The major cell wall component of Eubacteria is peptidoglycan, chains of polysaccharide cross-linked with short peptides. Peptidoglycan is not a component of any archaeal cell wall. Additionally, archaeal enzymes that are involved in protein synthesis have more in common with their eukaryotic counterparts than with eubacterial enzymes.

Archaea are also more commonly associated with extreme environments, such as frozen lakes in Antarctica and hot geysers in Yellowstone National Park. Those that live in more “normal” environments often have strange metabolisms when compared with Eubacteria.

- Eukaryotes have nuclear envelopes to surround their chromosomes, cytoskeleton to give the cells shape, and organelles such as endoplasmic reticulum, Golgi apparatus, lysosomes, mitochondria, and chloroplasts.

Unlike prokaryotes, which have no internal membrane structures, eukaryotes have extensive membranous components. Eukaryotic cells divide and conquer the various reactions taking place within the cell by designating specific membrane-bound organelles for specific functions. For example, mitochondria contain enzymes and proteins needed to break down and extract the energy stored within macromolecules. The energy released from the reactions of the mitochondria is then used to drive the synthesis of the major energy currency of the cell, called ATP (adenosine triphosphate).

The genetic material of eukaryotic cells is also separated from the rest of the cytoplasmic contents via the nuclear envelope. Because of this separation, the two parts of gene expression (transcription and translation) occur separately. Transcription is carried out within the nucleus and translation occurs on ribosomes in the cytoplasm and on some portions of the endoplasmic reticulum.

Eukaryotic cells also contain extensive internal protein networks, called the cytoskeleton, that aid in maintaining cell shape, and are involved in movement and other cellular processes, such as cell division and metabolism.

- Eukaryotes include a great variety of species that are classified into: kingdoms, phyla, class, order, family, followed by genus and species. The organism's scientific name is printed in text using the following format: *Genus species*.

Biologists attempt to classify organisms to better understand evolutionary relationships. A hierarchical scheme is used to classify all organisms. Each level of the hierarchy narrows the relationships until finally the two narrowest categories are reached: genus and species. The scientific name of an organism is derived from both the genus and species designations.

Traditionally, the eukaryotic domain was divided into four major kingdoms: animals, plants, fungi, and the artificially diverse protists. Some protists share features with animals, plants, and/or fungi, and sometimes were classified into separate miniature kingdoms. Great changes in classification have occurred for the protists and other eukaryotes, mostly due to molecular sequencing data of some genes.

Model Organism

- Model organisms are used to investigate how life exists, develops, and reproduces. Some model organisms include the bacterium *Escherichia coli*, yeast, *C. elegans*, *Drosophila*, zebrafish, *Xenopus*, and mice. In the plant world, *Arabidopsis* serves as the main model organism.
- Model organisms can be grown easily and reproduce fast, have their genomes completely sequenced, can be studied in each stage of their development, and are amenable to genetic manipulations.

Model organisms were usually chosen because they are more practical to study. This practicality is due to several model organism features, including ease of growth and an often quick reproduction. Usually, these organisms are already well-studied with abundant resources available to scientists regarding the organisms' genetics, metabolism, growth and development. Also, they can often be genetically manipulated to further increase understanding of life processes.

Bacteria are often used to study cell function and metabolism. Some bacteria, including *E. coli*, are even used during the genetic manipulation of other organisms.

C. elegans and *Drosophila* are used to study multicellularity. Vertebrate growth and development are often studied using zebrafish and *Xenopus*. Mice are used due to their uncanny likeness to humans regarding physiology and responses to diseases.

Even plants are not excluded from the model organism list. *Arabidopsis* is studied for plant genetics and molecular biology.

FOCUS ON RELEVANT RESEARCH

Selker, E. (2011) Neurospora. Curr. Biol. 21(4):R139–140.

Neurospora is a filamentous fungus commonly used as a model organism for genetics, biochemistry, population genetics, physiology, and cellular development. In the 1940's, *Neurospora crassa* was instrumental in developing the "one gene-one enzyme" hypothesis by Beadle and Tatum, which states that each gene within the organism's genome encodes only one enzyme involved in a biochemical reaction of the cell.

Other model organisms, such as *E. coli* and yeast, are more widely used instead of *Neurospora*. However, *Neurospora* still has advantages over the other, more popular, models. The ease of growth and storage, reproduction, and life cycle combined with the availability of mutant strains and appropriate technology for the fungus, make *Neurospora* an appealing biological model. Additionally, *Neurospora* contains higher-level eukaryotic features, that do not normally exist in simple systems. These organisms have elaborate systems to ensure their safety from invading pathogens.

Conceptual questions

1. Discuss some of the characteristics of model organisms.
2. Why might a researcher prefer a bacterium, such as *E. coli*, over *Neurospora*, a fungus?
3. When might a researcher prefer *Neurospora* rather than a bacterium, such as *E. coli*?

Discussion points

1. The "one gene-one enzyme" hypothesis proposed by Beadle and Tatum states that every gene in an organism encodes one enzyme that is used to catalyze specific cellular reactions. The Central Dogma of biology states that the flow of genetic information is from DNA to RNA and then to protein. Even though enzymes are proteins, not all proteins are enzymes. How might the "one gene-one enzyme" hypothesis be rewritten to reflect that not all genes encode enzymes?
2. Furthermore, some genes do not encode proteins. How might the Central Dogma be modified to reflect this new knowledge?
3. Consider the following hypothetical situation: A scientist is working out the genetics and specifics of a novel system that is believed to be involved in development. The organism that the scientist is working with is a multicellular eukaryote. The technology has not yet been invented to work within the experimental organism, so the scientist will need to use a model. Out of the models discussed in Chapter 1, which do you think might work out best for the researcher? Why? Can you think of a situation in which the researcher might want to use *E. coli* for some of the work?

DNA and Genetic Elements

- DNA isolation is a key technique used in molecular biology. The method involves removing the cellular proteins and RNA, leaving behind just the DNA.

The extraction and subsequent investigation of the DNA from model organisms and others is essential for molecular biology. DNA extraction techniques vary depending on the cell type and organism from which the DNA is extracted.

The general principle is that cells are burst, which not only releases DNA, but also RNA, proteins, lipids, and other cellular components. The DNA is then purified away from the cell debris by addition of detergents, enzymes that digest proteins, and other enzymes to digest RNA.

- Besides model organisms, a variety of gene creatures are studied in molecular biology. These include viruses, bacteriophage, viroids, plasmids, transposable elements, and prions. Although these have genetic material, they do not possess the ability to make their own proteins or exist without a host organism.

Gene creatures have genetic information but do not contain the cellular machines needed to grow, divide, and reproduce.

Viruses are composed of both nucleic acid and protein, but have to infect a host cell in order to reproduce.

Viroids and plasmids are genetic information that have the ability to self-replicate and exist within a host cell. Transposable elements can replicate, but must recombine with another self-replicating molecule.

Prions do not contain nucleic acid. They are misfolded versions of nerve tissue proteins that cause other proteins to misfold in the wrong three-dimensional shape as well. The misfolded proteins accumulate in the brains and spinal cords of animals and cause diseases such as bovine spongiform encephalopathy (mad cow disease).

were declining and now restricted to a significantly smaller range (Proc. Natl. Acad. Sci. USA *108*, 662). Looking for possible causes, the researchers found that the declining species had a significantly higher prevalence of infection with *Nosema*. They also discovered that the declining populations had reduced genetic diversity compared with the stable ones. Establishing causal links between these observations, however, will require further research, the authors say.

The authors also observe that the species affected by decline in North America have previously had a wide climatic range. By contrast, studies in Europe have found that species with a narrow climatic range are most at risk. This contrast suggests that different causes and mechanisms may be behind the decline on both continents.

The simultaneous threats to both the domesticated honey bees and the wild pollinators are bound to have repercussions throughout the natural environment and are also putting agricultural production and food supplies at risk. George McGavin commented: "The global threat to bees is a greater threat to our survival than global warming. This is a total ecological disaster we can avoid." Considering the scale of the industries affected, government spending on bee health has remained minuscule. McGavin calls the £1 million support that bee researchers get from the UK government "laughable". The EU has so far been inactive, but in January the European Commission acknowledged the importance of the problem and announced the installation of a European reference laboratory for bees' health to be based in France.

Tennekes concludes his analysis of the impact of neonicotinoids on wildlife in the Netherlands: "Ground and surface water contamination with persistent insecticides that cause irreversible and cumulative damage to aquatic and terrestrial (non-target) insects must lead to an environmental catastrophe. The data presented here show that it is actually taking place before our eyes, and that it must be stopped."

More research and political action is required to ensure that we don't, after all, experience what Rachel Carson anticipated 50 years ago: a silent spring.

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Quick guide

Neurospora

Eric U. Selker

What is* Neurospora*? *Neurospora* is the genus of a group of filamentous fungi but the word is most often used as a nickname for the best studied species, *N. crassa*, which has served as a model eukaryotic organism for nearly a century. The name *Neurospora* apparently came from the nerve-like stripes found on its sexual spores ('ascospores'; Figure 1). *Neurospora* is easily recognizable by its orange aerial asexual spores ('conidia').

What is its life style? The haploid vegetative filaments ('hyphae'), which look somewhat like axons (Figure 2), weave together to form a mat ('mycelium'). *Neurospora* grows at a prodigious rate — the mycelium advances at ~4 mm per hour in a reasonably warm environment if given some sugar, simple nutrients, and one vitamin (biotin). *N. crassa* is 'heterothallic' meaning that it has different subtypes ('mating types') that must find each other to enter the sexual phase of the life cycle. About 10 days later, its fruiting bodies ('perithecia') shoot the ascospores towards light. Germination of ascospores requires heat (for example, 65°C for an hour), which kills other cells in the neighborhood and accounts for reports of *Neurospora* in French bakeries in the 1800s and for the presence of *Neurospora* in burned sugar cane fields and burned forests in modern times.

What was* Neurospora *first known for? Research in the 1920s and 1930s revealed *N. crassa* to be a convenient and powerful genetic system; indeed it became a textbook example of first-division and second-division segregation, with easily demonstrable crossing over at the four-strand stage, and provided the first proof of gene conversion. The fact that it could be easily grown on defined media led to its adoption for the Nobel-prize winning 'one gene–one enzyme' work of Beadle and Tatum in the 1940s, which demonstrated that genes

Figure 1. A dissected perithecium of *N. crassa* with octets of ascospores (stripes not visible at this magnification) showing segregation of a color marker (courtesy of N. Raju).

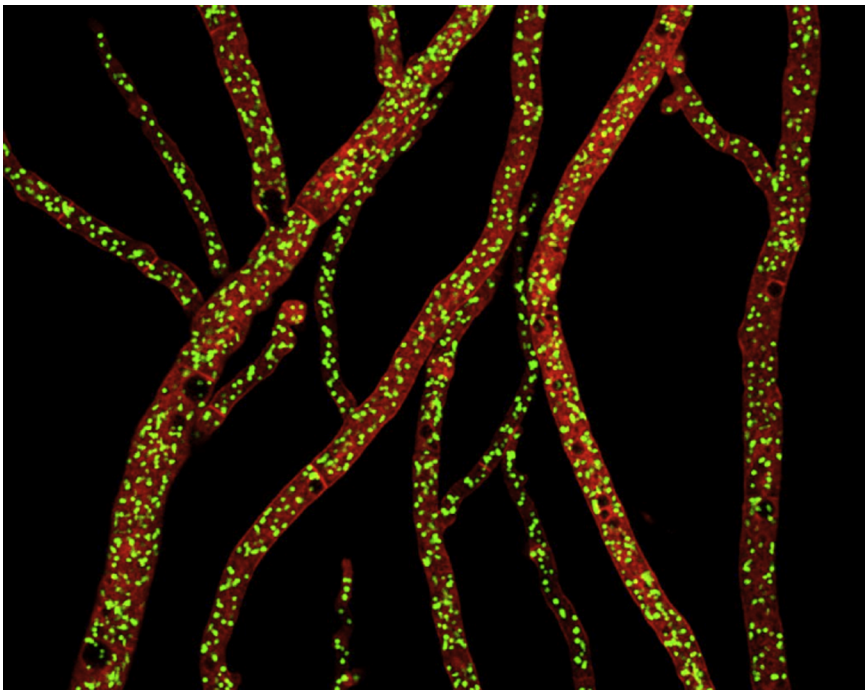

Figure 2. GFP-labeled histone H1 in *N. crassa* hyphae (courtesy of P. Hickey).

control biochemical processes. This and similar studies established the field of biochemical genetics and effectively initiated the discipline now known as molecular biology. Since then, *Neurospora* has served as a useful model in a large number of studies on problems in biochemistry, genetics, cell biology, development, physiology and population genetics, generally predating similar work with bacteria, yeasts, *Drosophila*, worms, mice, plants and other model systems.

Why is* Neurospora *still a favored model organism? Although *Escherichia coli* and yeast ultimately became more popular than *Neurospora* for studying many basic problems in molecular biology and genetics, *Neurospora* offers features not found in these and other eukaryotic systems. Thus, *Neurospora* is still regarded as an exemplary system for numerous genetic and molecular studies. Some of the reasons that it is an excellent model organism are: 1. *Neurospora* is easy to grow (in either liquid or solidified medium) and to store in suspended animation; 2. the haploid vegetative tissue is handy for scoring genetic traits and generating heterokaryons (strains with genetically distinct nuclei), useful for complementation tests; 3. *Neurospora*'s rapid and well-defined sexual cycle, compact genome with small, but cytologically recognizable, chromosomes that can be readily modified using either classical or molecular techniques makes the organism well-suited for genetic studies; 4. thousands of genes/mutations have been characterized and a high-quality genome sequence is available; 5. extensive collections of wild and constructed strains are readily obtainable, including knock-out mutants for the majority of known and predicted genes; 6. *Neurospora* sports features of higher eukaryotes that are absent from many other simple systems, for example DNA methylation and other 'epigenetic' marks, photobiology, circadian rhythms, gene silencing systems, cytoplasmic streaming, vegetative incompatibility reactions, morphogenesis; 7. modern tools are available for *Neurospora*, such as materials and methods to silence genes, to introduce genes at either homologous or non-homologous genomic sites and to perform proteomic studies; 8. the *Neurospora* community is unusually friendly and cooperative. It is noteworthy that a few talented, dedicated and altruistic *Neurospora* researchers, including the late David Perkins and the late Bob Metzenberg, were instrumental in publicizing the virtues of *Neurospora* while demonstrating that the use of *Neurospora* as a model system can be highly productive and fun. *Neurospora* meetings, which take place at Asilomar conference grounds in even years, typically draw 150–200 participants and welcome newcomers.

Can you tell me something wild about* Neurospora*? Starting with the discovery of 'repeat-induced point mutation' (RIP) more than two decades ago, *Neurospora* has revealed several remarkable and unexpected genetic mechanisms that serve to counter invasive DNA. RIP, which operates in the sexual phase of the life cycle in the period between fertilization and nuclear fusion, scans the haploid genome for duplicated sequences, such as those commonly resulting from the activity of transposable elements. Such sequences are then inactivated with multiple C to T mutations as well as with methylation of remaining cytosines. In addition, in vegetative cells, repeated sequences commonly generate aberrant RNAs that trigger silencing via an RNA interference (RNAi) mechanism called 'quelling'. Finally, in meiosis, unpaired sequences, such as those resulting from insertions or deletions in one parent, cause temporary silencing by another RNAi-based mechanism known as 'meiotic silencing by unpaired DNA' (MSUD).

Where can I find out more?

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