

Chapter 31

Fungi



Overview: Mighty Mushrooms

- The honey mushroom *Armillaria ostoyae* in Malheur National Forest in eastern Oregon is enormous.
 - Its subterranean mycelium covers 965 hectares, weighs hundreds of tons, and has been growing for 1,900 years.
- A hundred thousand species of fungi have been described, but it is estimated that there are actually as many as 1.5 million species of fungi.
 - Some fungi are single-celled, but most form complex multicellular bodies.
 - Fungal spores have been found 160 km above the ground.
- Fungi play important roles in ecosystems, decomposing dead organisms, fallen leaves, feces, and other organic materials.
 - This decomposition recycles vital chemical elements back to the environment in forms that other organisms can assimilate.
- Most plants depend on mutualistic fungi to help their roots absorb minerals and water from the soil.
- Humans have cultivated fungi for centuries for food, to produce antibiotics and other drugs, to make bread rise, and to ferment beer and wine.
- Some fungi cause diseases in plants and animals.

Concept 31.1 Fungi are heterotrophs that feed by absorption

- Fungi are heterotrophs that acquire their nutrients by absorption.

- Powerful hydrolytic enzymes secreted by the fungus break down food outside its body into simpler compounds that the fungus can absorb and use.
- Fungi then absorb small organic molecules from the surrounding medium.
- Other fungi use enzymes to penetrate the walls of plant cells, enabling the fungi to absorb nutrients from the plant cell.
- The absorptive mode of nutrition is associated with the ecological roles of fungi as decomposers, parasites, and mutualists.
 - Decomposer fungi break down and absorb nutrients from nonliving organisms.
 - Parasitic fungi absorb nutrients from the cells of living hosts.
 - Some parasitic fungi, including some that infect humans and plants, are pathogenic. Fungi cause 80% of plant diseases.
 - Mutualistic fungi also absorb nutrients from a host organism, but they reciprocate with functions that benefit their partner in some way.

The ecological success of fungi is partially due to a body structure that increases the efficiency of nutrient absorption.

- **Yeasts** are single-celled fungi, but most species of fungi are multicellular.
- The vegetative bodies of multicellular fungi are constructed of tiny filaments called **hyphae** that form an interwoven mat called a **mycelium** that infiltrates the material on which the fungus feeds.
 - Fungal mycelia can be huge, but they usually escape notice because they are subterranean.
- Fungal hyphae have cell walls built mainly of **chitin**, a strong but flexible nitrogen-containing polysaccharide identical to that found in arthropods.
- The filamentous structure of the mycelium provides an extensive surface area that suits the absorptive nutrition of fungi.
 - The structure of a mycelium maximizes the ratio of its surface area to its volume, making feeding very efficient.
 - One cm³ of rich organic soil may contain 1 km of fungal hyphae with a total surface area larger than 300 cm².
- A fungal mycelium grows rapidly, which is another adaptation for absorptive nutrition.
 - Proteins and other materials synthesized by the entire mycelium are channeled by cytoplasmic streaming to the tips of the extending hyphae.
- The fungus concentrates its energy and resources on adding hyphal length and absorptive surface area.
 - Although fungal mycelia are nonmotile, a fungus extends into new territory by swiftly extending the tips of its hyphae.
- Most fungi are multicellular with hyphae divided into cells by cross walls, or **septa**.
 - Septa generally have pores large enough for ribosomes, mitochondria, and even nuclei to flow from cell to cell.
- **Coenocytic fungi** that lack septa consist of a continuous cytoplasmic mass with hundreds or thousands of nuclei.
 - This mass results from repeated nuclear division without cytokinesis.
- Some fungi have specialized hyphae that allow them to feed on living animals.
 - Other parasitic fungi have specialized hyphae called **haustoria**, nutrient-absorbing hyphal tips that penetrate the tissues of their host.

- Mutually beneficial relationships between fungi and plant roots are called **mycorrhizae**.
- Mycorrhizal fungi can improve the delivery of phosphate ions and other minerals to plants because the vast mycelial networks of fungi can effectively acquire these minerals from the soil.
 - In exchange, the plants supply the fungi with organic nutrients such as carbohydrates.
- There are different types of mycorrhizal fungi.
 - **Ectomycorrhizal fungi** form sheaths of hyphae over the surface of the plant root and grow into the extracellular spaces of the root cortex.
 - **Arbuscular mycorrhizal fungi** extend their branching hyphae through the root cell wall and into tubes formed by invagination of the root cell membrane.
- Mycorrhizae are very important in natural ecosystems and agriculture.
 - Almost all vascular plants have mycorrhizae and rely on their fungal partners for essential nutrients.
- Foresters inoculate pine seedlings with ectomycorrhizal fungi to promote seedling growth.
 - In the absence of human intervention, mycorrhizal fungi colonize soils by spore dispersal, a key component of how fungi reproduce and spread to new areas.

Concept 31.2 Fungi produce spores through sexual or asexual life cycles

- Fungi reproduce by producing vast numbers of spores, either sexually or asexually.
 - The output of spores from one reproductive structure can be enormous: puffballs release trillions of spores in cloud-like bursts.
- Dispersed widely by wind or water, spores germinate to produce mycelia if they land in a moist place where there is food.
- The nuclei of fungal hyphae and the spores of most species are haploid, except for transient diploid stages that form during sexual life cycles.
- Sexual reproduction in fungi begins when hyphae from two genetically distinct mycelia release sexual signaling molecules called **pheromones**.
- Pheromones from each partner bind to receptors on the surface of the other, and the hyphae extend toward the source of the pheromones.
 - When the hyphae meet, they fuse.
- This mechanism contributes to genetic variation by preventing hyphae from fusing with other hyphae from the same mycelium or another genetically identical mycelium.
- The union of the cytoplasm of the two parent mycelia is known as **plasmogamy**.
- In many fungi, the haploid nuclei do not fuse right away.
 - Instead, parts of the mycelia contain coexisting, genetically distinct nuclei.
 - Such a mycelium is a **heterokaryon**.
- In some species, heterokaryotic mycelia become mosaics, with different nuclei remaining in separate parts of the same mycelium or mingling and even exchanging chromosomes and genes.
- In other fungi, the haploid nuclei pair off two to a cell, one from each parent.
 - Such a mycelium is called **dikaryotic**, meaning “two nuclei.”
- In many fungi with sexual life cycles, **karyogamy**, the fusion of haploid nuclei contributed by two parents, occurs well after plasmogamy, the cytoplasmic fusion of cells from the two parents.

- The delay may be hours, days, or even centuries.
- During karyogamy, the haploid nuclei contributed by the two parents fuse to produce diploid cells.
- In most fungi, the zygotes of transient structures formed by karyogamy are the only diploid stage in the life cycle.
- These zygotes undergo meiosis to produce haploid cells that develop as spores in specialized reproductive structures.
- The spores disperse to form new haploid mycelia.
- The sexual processes of karyogamy and meiosis generate genetic variation.
- The heterokaryotic condition also offers some of the advantages of diploidy, in that one haploid genome may be able to compensate for harmful mutations in the other.

The processes of asexual reproduction in fungi vary widely.

- 20,000 fungal species reproduce are only known to reproduce asexually.
- Some fungi reproduce by growing as filamentous fungi that produce haploid spores by mitosis.
 - Such species are known informally as **molds** if they form visible mycelia.
 - Molds typically grow rapidly and produce many spores asexually.
- Many species that produce asexual spores can also reproduce sexually if they encounter an individual of a different mating type.
- Other fungi reproduce asexually by growing as single-celled yeasts.
 - Instead of producing spores, yeasts reproduce asexually by simple cell division or by the pinching off of small “bud cells” from a parent cell.
- Many molds and yeasts have no known sexual stage.
- Such fungi were traditionally called **deuteromycetes**.
 - Whenever a sexual stage of a deuteromycete is discovered, the species is classified in a particular phylum depending on its sexual structures.
- Fungi can be identified from their sexual stages and by new genetic techniques.

Concept 31.3 The ancestor of fungi was an aquatic, single-celled, flagellated protist

- Data from paleontology and molecular systematics offer insights into the early evolution of fungi.
- Systematists recognize that the kingdoms Fungi and Animalia are more closely related to each other than they are to plants or other eukaryotes.

DNA comparisons may provide clues about fungal origins.

- Phylogenetic systematics suggests that fungi evolved from a unicellular, flagellated protist.
 - The lineages of fungi that diverged earliest (the chytrids) have flagella.
 - Most of the protists that share a close common ancestor with animals and fungi possess flagella.
- DNA sequence data indicate that fungi, animals, and their protist relatives form a clade called **opisthokonts**, a name that refers to the posterior (*opistho-*) location of the flagellum.

- DNA sequence data also indicate that fungi are more closely related to several groups of single-celled protists than to animals, suggesting that the ancestor of fungi was unicellular.
 - One such single-celled group, the **nucleariids**, consists of amoebae that feed on algae and bacteria.
- Animals are more closely related to a *different* group of protists, the choanoflagellates.
 - These findings suggest that animals and fungi evolved multicellularity independently.
- Scientists estimate that the ancestors of animals and fungi diverged into separate lineages about 1-1.5 billion years ago.
- The oldest undisputed fungal structures are only 460 million years old.
 - It is likely that the first fungi were unicellular and did not fossilize.

Microsporidia may be fungi.

- Microsporidia are unicellular parasites of animals and protists, often used in the biological control of insect pests.
 - Although they do not normally infect humans, microsporidia pose a health risk to people with AIDS and other immune-compromised conditions.
- Microsporidia lack conventional mitochondria and represent something of a taxonomic mystery.
- Some researchers suggest that they are a basal lineage of eukaryotes.
- In recent years, researchers have discovered that microsporidia have tiny organelles derived from mitochondria.
- Most molecular comparisons indicate that microsporidia are highly-derived parasitic fungi.
- A 2006 analysis of DNA sequence data from six genes in nearly 200 fungal species indicates that microsporidia are members of an early-diverging lineage of fungi.
 - Data from additional genes are needed to resolve whether microsporidia are fungi or a closely related but distinct group of organisms.

Fungi underwent an adaptive radiation when life colonized land.

- Much of the modern diversity of fungi may have originated during an adaptive radiation that began when multicellular life colonized land.
- Fossils of the first vascular plants from the late Silurian period (420 million years ago) contain evidence of mycorrhizae.
 - This evidence includes fossils showing hyphae that have penetrated within plant cells and formed structures that closely resemble the haustoria of arbuscular mycorrhizae.
- Plants likely existed in beneficial relationships with fungi from the earliest periods of colonization of land.

Concept 31.4 Fungi have radiated into a diverse set of lineages

- The phylogeny of fungi is currently the subject of much research.
 - In the past decade, molecular analyses have helped clarify the evolutionary relationships between fungal groups, although there are still areas of uncertainty.

Chytrids diverged early in fungal evolution.

- Fungi classified in the phylum Chytridiomycota, called the **chytrids**, are ubiquitous in lakes and soil.
- Some chytrids are decomposers, while others parasitize protists, fungi, plants, and animals.
 - One chytrid parasite has likely contributed to the global decline of amphibian populations.
- Some chytrids are important mutualists.
 - For example, anaerobic chytrids that live in the digestive tracts of sheep and cattle help break down plant matter.
- Molecular evidence supports the hypothesis that chytrids diverged early in fungal evolution.
- Like other fungi, chytrids use an absorptive mode of nutrition, have chitinous cell walls, and have similar key enzymes and metabolic pathways.
- Although a few chytrids are unicellular, most form coenocytic hyphae.
- Chytrids are unique among fungi in having flagellated spores, called **zoospores**.

Zygomycetes form resistant structures during sexual reproduction.

- The 1,000 species of **zygomycetes** exhibit considerable diversity.
- The phylum includes fast-growing molds, parasites, and commensal symbionts of animals.
- The life cycle and biology of *Rhizopus stolonifer*, black bread mold, are typical of zygomycetes.
- The hyphae are coenocytic, with septa found only where reproductive cells are formed.
 - Horizontal hyphae spread out over food, penetrate it, and digest nutrients.
- In the asexual phase, hundreds of haploid spores develop in sporangia at the tips of upright hyphae.
 - Within each sporangium, hundreds of haploid spores develop and are dispersed through the air.
 - Spores that happen to land on moist food germinate, growing into new mycelia.
- If environmental conditions deteriorate or food is depleted, *Rhizopus* may reproduce sexually.
- Plasmogamy of opposite mating types produces a **zygosporangium** within which karyogamy and then meiosis occur.
- Although the zygosporangium represents the zygote ($2n$) stage in the life cycle, it is not a zygote in the sense of a cell with one diploid nucleus.
 - The zygosporangium is a multinucleate structure, first heterokaryotic with many haploid nuclei from the two parents and then with many diploid nuclei after karyogamy.
- Zygosporangia are resistant to freezing and drying and are metabolically inactive.
 - When conditions improve, a zygosporangium undergoes meiosis, germinates into a sporangium, and releases genetically diverse haploid spores that colonize new substrates.
 - Some zygomycetes, such as *Pilobolus*, actually “aim” and shoot their sporangia toward bright light.

Glomeromycetes form a separate clade.

- Recent molecular studies, including a phylogenetic analysis of DNA sequence data from hundreds of fungal species, indicate that glomeromycetes form a separate clade.
- Despite their small numbers, with 160 identified species, glomeromycetes are an ecologically significant group.

- Nearly all glomeromycetes form arbuscular mycorrhize.
 - The tips of the hyphae that push into plant root cells branch into tiny treelike structures known as arbuscles.
 - Such mutualistic partnerships with glomeromycetes are present in 90% of all plants.

Ascomycetes are sac fungi that produce sexual spores in saclike asci.

- Mycologists have described more than 65,000 species of **ascomycetes**, or sac fungi, from a variety of marine, freshwater, and terrestrial habitats.
- Ascomycetes produce sexual spores in saclike **asci** and are called *sac fungi*.
- Most ascomycetes bear their sexual stages in fruiting bodies called **ascocarps**, which range in size from microscopic to macroscopic.
 - The spore-forming asci are found in the ascocarps.
- Ascomycetes range in size and complexity from unicellular yeasts to elaborate cup fungi and morels.
- Some ascomycetes are devastating plant pathogens, while many are important decomposers, particularly of plant material.
- More than 25% of ascomycete species live with green algae or cyanobacteria in mutualistic associations called lichens.
 - Some ascomycetes form mycorrhizae with plants or live between mesophyll cells in leaves, where they may help protect the plant tissue from insects by releasing toxins.
- The bread mold *Neurospora crassa* illustrates some of the reproductive features and processes in ascomycete fungi.
- Ascomycetes reproduce asexually by producing enormous numbers of asexual spores called **conidia**.
 - Conidia develop in long chains or clusters at the tips of specialized hyphae called conidiophores. Once released, they are dispersed by the wind.
- In *Neurospora*, conidia may also be involved in sexual reproduction, fusing with hyphae from a mycelium of a different mating type.
- Fusion of two different mating types is followed by plasmogamy, resulting in the formation of dikaryotic cells, each with two haploid nuclei representing the two parents.
- The cells at the tips of these dikaryotic hyphae develop into many asci.
- Within each ascus, karyogamy combines the two parental genomes, and then meiosis forms four genetically different nuclei.
 - This process is usually followed by a mitotic division, which forms eight ascospores.
 - The ascospores develop in and are eventually discharged from the ascocarp.
- In contrast to the life cycle of zygomycetes, the extended dikaryotic stage of ascomycetes provides increased opportunity for genetic recombination.
 - In *Neurospora*, many dikaryotic cells can develop into asci, recombining genomes and resulting in a multitude of genetically different offspring from one mating event.
- *Neurospora* has played an important role in biological research.
 - In the 1930s, biologists used *Neurospora* to formulate the one gene–one enzyme hypothesis.
- Today, *Neurospora* serves as a model organism.

- In 2003, its entire genome was published. With 10,000 genes, the genome of this tiny fungus is three-fourths the size of the *Drosophila* genome and one-third the size of the human genome.
- The *Neurospora* genome is compact, with few stretches of noncoding DNA.
- *Neurospora* may have a genomic defense system to prevent “junk DNA” such as transposons from accumulating in its genome.

Basidiomycetes or club fungi have long-lived dikaryotic mycelia.

- Approximately 30,000 fungi, including mushrooms, puffballs, and shelf fungi, are called **basidiomycetes** and are classified in the phylum Basidiomycota.
- The name of the phylum is derived from the **basidium**, a cell in which karyogamy occurs, immediately followed by meiosis.
 - The club-like shape of the basidium is responsible for the common name *club fungus*.
- Basidiomycetes are important decomposers of wood and other plant material.
 - Of all fungi, the basidiomycetes are best at decomposing the complex polymer lignin, which is abundant in wood.
 - Many shelf fungi break down the wood of weak or damaged trees and continue to decompose the wood after the tree dies.
- The life cycle of a basidiomycete usually includes a long-lived dikaryotic mycelium.
 - As in ascomycetes, this extended dikaryotic stage provides opportunities for genetic recombination.
- Environmental cues induce the dikaryotic mycelium to reproduce sexually by producing elaborate fruiting bodies called **basidiocarps**.
- A mushroom is a familiar basidiocarp that can pop up overnight as it absorbs water and as cytoplasm streams in from the dikaryotic mycelium.
 - The dikaryotic mycelia are long-lived, generally producing a new crop of basidiocarps each year.
 - A “fairy ring” of mushrooms appears as the underground mycelium expands outward at a rate of about 30 cm per year, decomposing organic matter in the soil.
 - Some giant fairy rings are produced by mycelia that are centuries old.
- The cap of a mushroom supports and protects a large surface area of dikaryotic basidia on gills.
- The basidia form sexual spores called basidiospores.
- During karyogamy, the two nuclei in each basidium fuse to produce a diploid nucleus.
- The diploid nucleus in each basidium undergoes meiosis, producing four haploid nuclei.
- Each basidium then grows four appendages, and one haploid nucleus enters each one.
- Each appendage develops into a basidiospore.
- A common white, store-bought mushroom has a gill surface area of about 200 cm² and may release a billion basidiospores, which drop from the cap and blow away.

Concept 31.5 Fungi play key roles in nutrient cycling, ecological interactions, and human welfare

Ecosystems depend on fungi as decomposers, mutualists, and pathogens.

- Fungi are important decomposers of organic material, including the cellulose and lignin of plant cell walls.
 - Almost any carbon-containing substrate—including jet fuel and house paint—can be consumed by a fungus.
 - Researchers are exploring how fungi can be used in bioremediation projects.
- Fungi and bacteria are essential for providing ecosystems with the inorganic nutrients responsible for plant growth.
 - Without decomposers, carbon, nitrogen, and other elements would become tied up in organic matter.
- Fungi form symbiotic relationships with plants, algae, cyanobacteria, and animals.
 - All of these relationships have profound ecological effects, often affecting the growth, survival, or reproduction of many species in a community.
- Most vascular plants form mutualistic associations with mycorrhizal fungi. These mycorrhizae are extremely important in natural ecosystems and agriculture.
- In addition, all plant species studied to date harbor symbiotic **endophytes**, fungi that live inside leaves and other plant parts without causing harm.
 - Most endophytes are ascomycete fungi.
 - Some endophytes produce toxins that deter herbivores.
 - Other endophytes increase host plant tolerance of heat, drought, or heavy metals.
- Researchers investigating the cacao tree, *Theobroma cacao*, found that endophytes of woody flowering plants play an important role in defending against pathogens.

Fungi and animals may be mutualistic symbionts.

- Some fungi break down plant material in the guts of cows and other grazers.
- Many species of ants and termites raise fungi in “farms” and feed them leaves.
 - The fungi break the leaves down into a substance that the insects can digest and feed the ants with specialized swollen hyphal tips that are rich in proteins and carbohydrates.
- Some mutualistic associations between “farmer” insects and “farmed” fungi have been established for more than 50 million years.
 - In many cases, the fungi can no longer survive without the insects.

Lichens are symbiotic associations of photosynthetic microorganisms and fungi.

- **Lichens** are symbiotic associations of millions of photosynthetic microorganisms held in a mass of fungal hyphae.
- The fungal component is commonly an ascomycete, but one glomeromycete and 75 basidiomycete lichens are known.
- The photosynthetic partners are usually unicellular or filamentous green algae or cyanobacteria.
 - The fungal hyphae provide most of the lichen’s mass and give it an overall shape and structure.
 - The algae or cyanobacteria usually occupy an inner layer below the lichen surface.
- The merger of fungus and algae is so complete that they are actually given genus and species names as though they were single organisms.
- 17,000 species of lichen have been described—one in seven of all known fungi.
- Asexual reproduction of lichens as a symbiotic unit is common.

- This occurs by fragmentation of the parental lichen or by the formation of **soredia**, small clusters of hyphae with embedded algae.
- The fungi of many lichens also reproduce sexually, and lichen algae can reproduce independently of the fungus by asexual cell division.
- In most lichens, each partner provides things the other could not obtain on its own.
 - For example, the alga provides the fungus with carbon compounds.
 - The cyanobacteria provide organic nitrogen through nitrogen fixation.
 - The fungus provides a suitable physical environment for growth, retaining water and minerals, allowing for gas exchange, protecting the photosynthetic partner, secreting acids that aid in the uptake of minerals, and deterring consumers with toxic compounds.
- Lichens are important pioneers on newly cleared rock and soil surfaces, such as burned forests and volcanic flows.
- The lichen acids penetrate the outer crystals of rocks and help break down the rock.
 - This breakdown allows the trapping of soil and starts the process of succession.
- Lichens may have aided the colonization of land by plants.
 - Fossils of lichens or lichen-like organisms date to 550-600 million years ago, long before plants grew on land.
 - Early lichens may have modified rocks and soil much as they do today, helping to pave the way for the growth of the first land plants.
- Lichens are particularly sensitive to air pollution, and their deaths can serve as an early warning of deteriorating air quality.

Some fungi are pathogens.

- About 30% of the 100,000 known species of fungi are pathogens or parasites, mostly of plants.
- *Cryphonectria parasitica*, the ascomycete that causes chestnut blight, was introduced into the United States on nursery trees sent from Asia in the early 1900s.
 - Fungal spores enter cracks in the bark of American chestnut trees and produce hyphae, killing the tree.
 - American chestnuts once were common in many forests in eastern North America, but now they typically persist only as sprouts from the stumps of former trees.
- Another ascomycete, *Fusarium circinatum*, causes pitch pine canker, a disease that threatens pines throughout the world.
- Major losses of fruit and grains each year are due to fungi.
- Some fungi that attack food crops produce compounds that are toxic to humans.
- The mold *Aspergillus* can contaminate improperly stored grains and peanuts with carcinogenic aflatoxins.
- Poisons produced by ergots of the ascomycete *Claviceps purpurea* can cause ergotism when infected rye is milled into flour and consumed.
 - Ergotism is characterized by gangrene, nervous spasms, burning sensations, hallucinations, and temporary insanity.
 - An epidemic of ergotism in around A.D. 944 killed more than 40,000 people in France.
 - One of the compounds isolated from ergots is lysergic acid, the raw material from which the hallucinogen LSD is made.
- Animals are much less susceptible to parasitic fungi than are plants.

- 500 fungal species are known to parasitize humans and other animals, but these few species do considerable damage.
- The chytrid *Batrachochytrium dendrobatidis* may be responsible for the recent decline or extinction of about 200 species of frogs and other amphibians.
 - Field observations and studies of museum specimens indicate that *B. dendrobatidis* first appeared in frog populations shortly before their declines in Australia, Costa Rica, and the United States.
- In regions where it infects frogs, this chytrid has very low levels of genetic diversity.
 - These findings are consistent with the hypothesis that *B. dendrobatidis* has emerged recently and spread rapidly across the globe, leading to the sudden decline of numerous amphibian populations.
- The general term for a fungal infection is **mycosis**.
 - Infections of ascomycetes produce the disease ringworm, known as athlete's foot when the ascomycetes grow on the feet.
- Systemic mycoses spread through the body and cause very serious illnesses. These mycoses are typically caused by inhaled spores.
 - Coccidioidomycosis is a systemic mycosis that produces tuberculosis-like symptoms in the lungs.
- Some mycoses are opportunistic, occurring only when a change in the body's microbiology, chemistry, or immunology allows the fungi to grow unchecked.
 - *Candida albicans* is a normal inhabitant of moist epithelia such as human vaginal lining, but it can become an opportunistic pathogen, leading to so-called "yeast infections."
 - Other opportunistic mycoses have become more common due to AIDS, which weakens the immune system.

Fungi are commercially important.

- In addition to the benefits that we receive from fungi in their roles as decomposers and recyclers of organic matter, we use fungi in a number of ways.
- Most people eat mushrooms, the fruiting bodies (basidiocarps) of subterranean fungi.
- The distinctive flavors of Roquefort and other blue cheeses are due to the fungi used to ripen them.
- Morels and truffles, the fruiting bodies of various ascomycetes, are prized by gourmets for their complex flavors.
 - Truffles release strong odors that may mimic the sex attractants of certain mammals.
 - Several European truffles mimic the sex attractants released by male pigs. As a result, *female* pigs are used to sniff out these delicacies.
- Yeasts are very important in food production. Humans have used yeasts to produce alcoholic beverages and make bread rise for thousands of years.
- Under anaerobic conditions, yeasts ferment sugars to alcohol and CO₂, which leavens dough.
 - The yeast *Saccharomyces cerevisiae* is the most important of all cultured fungi and is available in many strains as baker's and brewer's yeast.
- Contributing to medicine, some fungi produce antibiotics used to treat bacterial diseases.
 - The first antibiotic discovered was penicillin, made by the common mold *Penicillium*.
 - A compound extracted from ergots is used to reduce high blood pressure and stop maternal bleeding after childbirth.
- Fungi play an important role in research in molecular biology and biotechnology.

- Researchers use *Saccharomyces* to study the molecular genetics of eukaryotes.
 - Scientists have learned about the genes involved in Parkinson's and Huntington's diseases by examining the homologous genes in *Saccharomyces*.
- Genetically modified fungi are used to produce human glycoproteins.
 - In 2003, scientists succeeded in engineering a strain of *S. cerevisiae* that produces human glycoproteins, including insulin-like growth factor.
- Researchers are sequencing the genome of the wood-digesting basidiomycete *Phanerochaete chrysosporium*, one of many "white rot" fungi, in order to decipher the metabolic pathways by which white rot breaks down wood, with the goal of harnessing these pathways to produce paper pulp.