### ➢ *Modern classification of living organisms*

***Whittaker (1969)*** suggested the classification of living organisms into five kingdoms: Monera, Protista, Fungi, Animalia, and Plantae. The three-domain system is a biological classification introduced by Carl Woese et al. in 1990, which divides cellular life forms into the domains Archaea, Bacteria, and Eukaryotes. The main difference from previous classifications is the separation of Archaea from Bacteria.

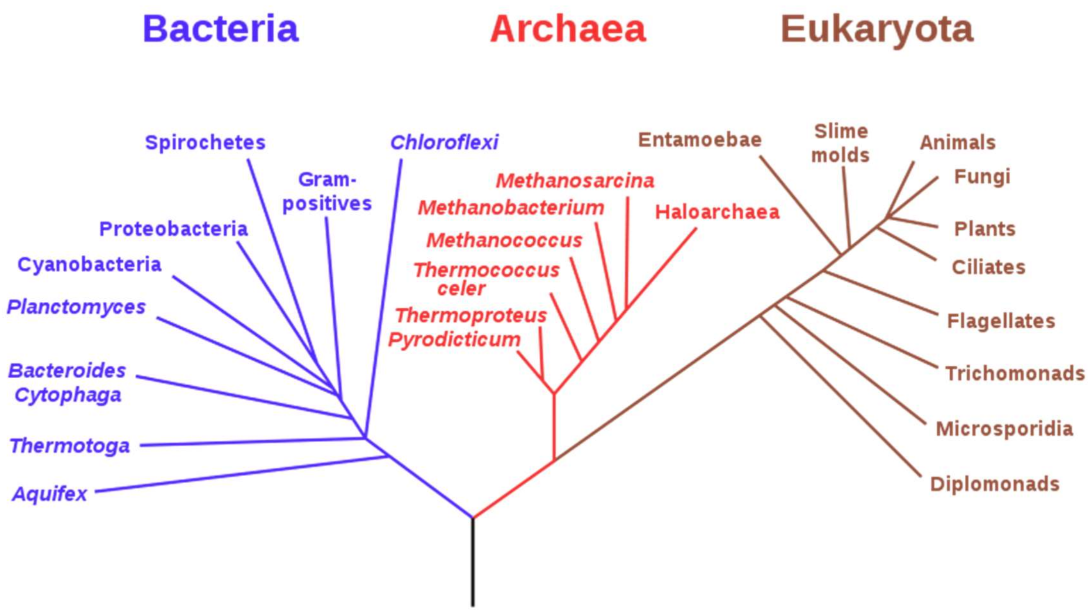



Figure 2.1 **:** *A phylogenetic tree of living organisms, based on RNA data and proposed by Carl Woese (Carl Woese et al. 1990), showing the separation of Bacteria, Archaea, and Eukaryotes. Trees constructed with other genes are generally similar, although they may place some early-branching groups very differently due to long branch attraction. The exact relationships of the three domains are still debated, as is the position of the root of the tree. It has also been suggested that due to lateral gene transfer, a tree may not be the best representation of the genetic relationships of all organisms. For example, some genetic evidence suggests that eukaryotes developed from the union of certain bacteria and archaea (one becoming an organelle and the other the main cell).*

Cavalier-Smith and his collaborators revised their classification in 2015. In this scheme, they introduced two superkingdoms, Prokaryota and Eukaryota, as well as seven kingdoms. The Prokaryota include two kingdoms: Bacteria and Archaea. (This was based on the consensus in the Taxonomic Outline of Bacteria and Archaea, and the Catalogue of Life). The Eukaryota include five kingdoms: Protozoa, Chromista, Plants, Fungi, and Animals. In this classification, a protist is one of the unicellular eukaryotic organisms. This classification will be used for the rest of the course.

## *I. Super-kingdom Prokaryota*

Prokaryotes are unicellular organisms characterized by the absence of a nucleus enclosed by a membrane and the absence of other membrane-bound cellular organelles, such as mitochondria or chloroplasts. Their genetic material is usually in the form of circular DNA, located in a region called the nucleoid.

Prokaryotes are the dominant living beings on Earth, possibly present for three-quarters of Earth's history, and have managed to adapt to almost all available ecological habitats. As a group, they exhibit extremely diverse metabolic capabilities and can use almost any organic compound, as well as some inorganic compounds, as a food source.

This super-kingdom includes two main kingdoms: ***Bacteria*** and **Archaea**. They are ubiquitous in various environments, from soils to oceans, and play essential roles in biological processes such as nutrient cycling and the decomposition of organic matter.

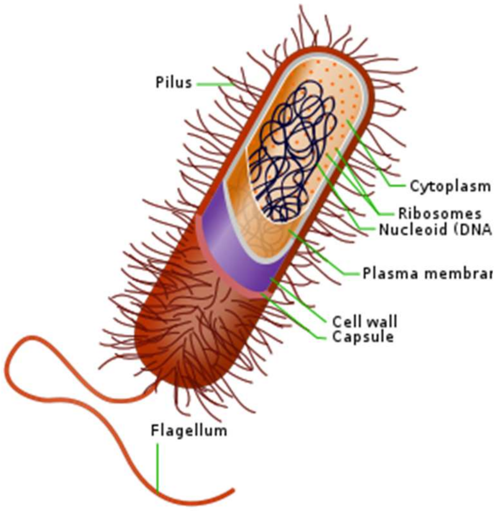



Figure 2.2 : Figure of a typical prokaryotic cell.

*Own work using: Biology 10e Textbook (chapter 4, p. 63) by: Peter Raven, Kenneth Mason, Jonathan Losos, Susan Singer · McGraw-Hill Education.*

### *1. Bacteria Kingdom*

Bacteria, members of a group of microscopic unicellular organisms, exist in immense numbers in nearly all environments on Earth, from deep-sea hydrothermal vents to underground depths and the digestive tracts of humans.

Bacteria lack a membrane-bound nucleus and other internal structures, classifying them as unicellular life forms known as prokaryotes. Some bacteria can cause diseases in humans, animals, or plants, but most are harmless and serve as beneficial ecological agents whose metabolic activities support higher life forms. Other bacteria form symbiotic relationships with plants and invertebrates, performing essential functions for their hosts, such as nitrogen fixation and cellulose degradation.

Without prokaryotes, soil would not be fertile, and dead organic matter would decompose much more slowly. Some bacteria are widely used in the production of food, chemicals, and antibiotics.

Bacteria are also distinguished by the presence of cell walls composed of peptidoglycan, a substance containing muramic acid, which provides structural strength and forms a protective layer around the cell membrane. Studies on the relationships between different bacterial groups continue to provide new insights into the origins of life on Earth and the mechanisms of evolution.

### *1.2 Cyanobacteria (Phylum Not Belonging to the Plant Kingdom)*

Cyanobacteria, also known as *Cyanobacteriota* or *Cyanophyta*, are a phylum of gram-negative autotrophic bacteria that can obtain biological energy through photosynthesis. The name "cyanobacteria" refers to their color (from the Ancient Greek *κύανος* (*kúanos*) meaning "blue"), which also forms the basis of their common name, blue-green algae, although they are not scientifically classified as algae. They are believed to have originally evolved in freshwater or terrestrial environments.

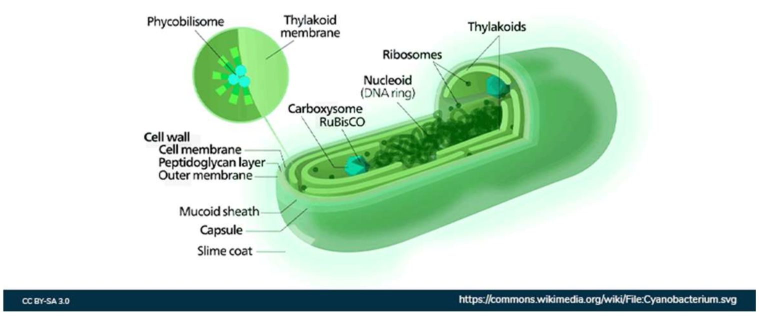



Figure 2.3: Figure of a cyanobacteria.

### *1.2.1 Cyanobacteria autotrophic organisms*

Cyanobacteria use photosynthetic pigments, primarily chlorophyll a and phycobilins, to convert light energy into chemical energy. Some specialized species also contain chlorophyll d. Unlike heterotrophic prokaryotes, cyanobacteria have internal membranes. These are flattened sacs called thylakoids, where photosynthesis takes place.

### *1.2.2 Importance of Cyanobacteria*

In addition to their ecological importance, cyanobacteria are also valuable in various fields, particularly in biotechnology for biomass production, in agriculture for atmospheric nitrogen fixation, and even in medicine for the production of active substances.

☞ ***Example : Spirulina***

**Spirulina** is a cyanobacterium (also known as a cyanophyte or blue-green alga) belonging to the *Arthrospira* genus. It is a unicellular photosynthetic microorganism with a spiral shape, which gives it its name. Spirulina is often considered a **superfood** due to its rich nutritional composition, including proteins, vitamins, minerals, and antioxidants. It is known for its **high protein content** (up to 70% of its dry weight), essential amino acids, and **bioactive compounds** that support immune function and overall health.

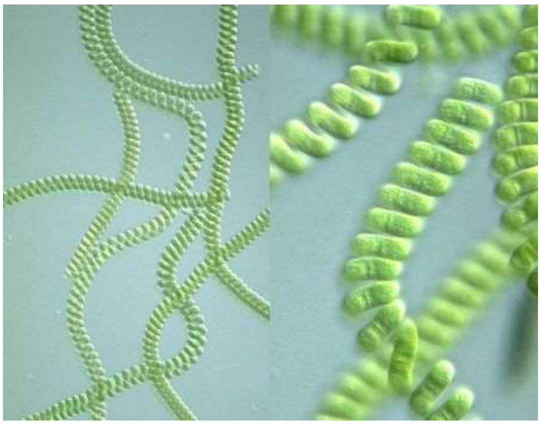


Figure 2.4: Spirulina on microscope *https://miimosa.com/projects/spiruline-locale-pour-une-spirale-humaine-dans-le-monde ty*

Due to its **antioxidant and anti-inflammatory properties**, spirulina is used in **nutritional supplements**, functional foods, and even cosmetics. It is also explored for its potential in **sustainable food production**, as it grows rapidly with minimal resources, making it an eco-friendly protein source. Additionally, some studies suggest that spirulina may help with **detoxification, blood sugar regulation, and cardiovascular health**. However, some species of cyanobacteria can produce toxins that are potentially dangerous to human and animal health when they proliferate in water, posing a risk to water quality and food safety.

### *2. Archaea*

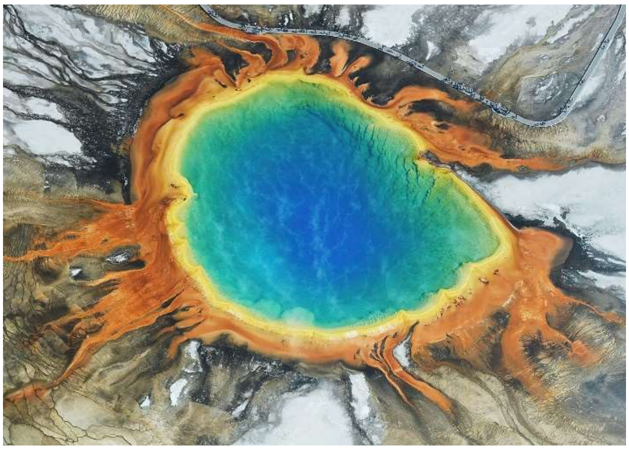


Figure 2.5: Yellowstone National Park, USA. Carsten Steger.

- Archaea are a distinct domain of unicellular microorganisms. They are characterized by their unique cell structure, lacking a nucleus and membrane-bound organelles, which classifies them as prokaryotes. Though initially grouped with bacteria, they are now recognized as a separate domain of life.
- Archaea exhibit great metabolic diversity and can survive in extreme environments, such as hot springs, salt lakes, and acidic soils. They utilize a variety of energy sources, ranging from organic compounds to metals and even hydrogen.
- Although they resemble bacteria in appearance, archaea share certain metabolic features with eukaryotes, particularly in transcription and translation processes. Additionally, their membrane lipid structure is unique, characterized by the use of ethers instead of esters. Unlike bacteria, archaea lack muramic acid in their cell walls.
- Archaea play a crucial role in terrestrial and aquatic ecosystems, contributing to processes such as carbon fixation, the nitrogen cycle, and maintaining the health of various microbiomes, including those found in the human digestive tract.

## *II. The super-kingdom Eukaryota*

- ***Fungi Kingdom – General characteristics***

In botanical terms, fungi are referred to as *Fungi*. They are a group of eukaryotic organisms that include microorganisms such as yeasts and molds, as well as more familiar mushrooms. Unlike plants, fungi have cell walls composed of *chitin* rather than *cellulose*. They are *heterotrophic* organisms, obtaining nutrients through absorption, and can be *saprotrophic* (decomposers), *parasitic*, or *mutualistic*. Fungi reproduce primarily through *spores*, which can be produced sexually or asexually. The branch of biology dedicated to the study of fungi is known as mycology (from the Greek *μύκης mykes*, meaning fungus). In the past, mycology was considered a branch of botany, but it is now known that fungi are genetically more closely related to animals than to plants.

Structurally, fungi are often characterized by filamentous vegetative structures called *hyphae* (singular: *hypha*), which, when grouped into a coherent and macroscopically visible mass, form a *mycelium*. Hyphae can be **septate** (divided by cross-walls) or **coenocytic** (lacking cross-walls), and they grow at their tips, enabling rapid colonization of substrates. When these filaments are fused and/or tightly interwoven, the structure is called *plectenchyma*. Since the vegetative body lacks differentiated leaves or roots, it is referred to as a *thallus*.

A distinguishing characteristic that sets fungi apart from plants, bacteria, and certain protists is the presence of *chitin* in their cell walls. Unlike plants, fungi do not photosynthesize; like animals, they are *heterotrophic*, acquiring nutrients by absorbing dissolved molecules, usually by secreting digestive enzymes into their environment. As a result, they play a crucial role as **decomposers** in ecosystems. Some fungi also form **mutualistic relationships**, such as **mycorrhizae** with plant roots or **lichens** with algae or cyanobacteria.

Fungi can reproduce **both sexually and asexually**, typically through the production of **spores**, which are released into the environment and dispersed by air or water. Asexual reproduction often occurs through **sporangia** or **conidia**, while sexual reproduction usually involves the fusion of *hyphae* to form specialized reproductive structures, such as **fruiting bodies** (e.g., mushrooms).

Beyond their ecological importance, fungi have significant applications in **biotechnology and industry**, including antibiotic production (e.g., penicillin), fermentation (e.g., bread, beer, and cheese), and enzyme production for various biotechnological processes.

### *1.1 Systematic complexity in Fungi*

These differences, among others, place fungi in a unique group of related organisms called *Eumycota* (true fungi or *Eumycetes*), which share a common ancestor, meaning they form a *monophyletic group*. This interpretation is strongly supported by **molecular phylogenetics**. This fungal group is distinct from **Myxomycetes** (slime molds) and **Oomycetes** (water molds), which have similar structural characteristics but belong to completely different evolutionary lineages. *Myxomycetes* are now classified under **Amoebozoa**, while *Oomycetes* belong to **Stramenopiles (Heterokonta)**, making them more closely related to algae than to true fungi.

The kingdom *Fungi* encompasses an enormous diversity of taxa with varied ecologies, life cycle strategies, and morphologies, ranging from unicellular aquatic *Chytridiomycota* to large mushrooms. However, the true biodiversity of the fungal kingdom remains largely unknown, with estimates ranging between **2.2 and 3.8 million species** (*Hawksworth & Lücking, 2017*). Among these, only about **150,000 species** have been formally described, with more than **8,000 species known to be harmful to plants** and at least **300 species identified as human pathogens**.

Since the pioneering taxonomic work of the **18th and 19th centuries** by *Carl Linnaeus, Christiaan Hendrik Persoon*, and *Elias Magnus Fries*, fungi have been classified based on their **morphology** (e.g., spore color, microscopic structures) and **physiology**. However, advances in **molecular genetics** have introduced **DNA-based analysis** into fungal taxonomy, sometimes challenging traditional classifications based on morphology. **Phylogenetic studies** published in the early 21st century have significantly reshaped fungal classification.

#### Current Major Phyla of Fungi:

1. **Chytridiomycota** (chytrids – primarily aquatic, flagellated spores)
2. **Blastocladiomycota** (similar to chytrids but with distinct life cycles)

3. **Zoopagomycota** (mainly parasites or symbionts of animals and protists)
4. **Mucoromycota** (includes many common molds and mycorrhizal fungi)
5. **Ascomycota** (sac fungi – includes yeasts, molds, and truffles)
6. **Basidiomycota** (club fungi – includes mushrooms, puffballs, and rusts)
7. **Microsporidia** (unicellular, obligate intracellular parasites, sometimes considered a separate group but molecular evidence places them within Fungi)

Several characteristics of fungi, although secondarily lost in some taxa, help group various organisms within the **phylogeny of Eukaryotes**. These organisms, represented in orange in *Figure 3.1*, include both *Oomycetes* and *Eumycetes*, forming a *polyphyletic group*. However, the use of the term *fungus* for a polyphyletic group is debated. Some researchers, such as *Lecointre & Le Guyader (2016)* in their book *"Classification phylogénétique du vivant, Tome 1"*, propose restricting the term *fungi* to *Eumycetes* and their sister taxon, *Microsporidia*, thereby excluding *Oomycetes* and *Myxomycetes*, in line with modern phylogenetic classification.

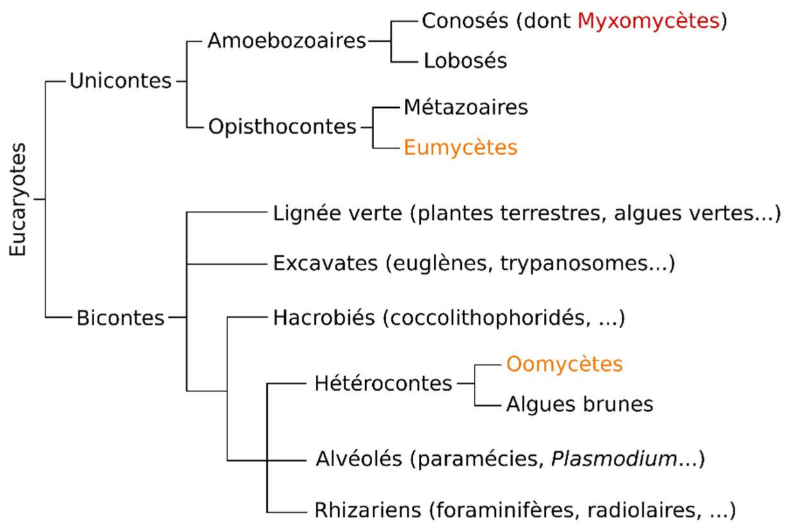



Figure 3.1 – Simplified phylogenetic tree of Eukaryotes

*The groups in orange are those grouped under the name "fungus" (in the broad sense). According to Lecointre and Le Guyader (2016).*

In this context, the term **"fungus"** (in its broad sense) is used to encompass all **filamentous and absorptive** life forms, including **Oomycetes** and **Eumycetes**. However, **"true fungi"** (in the strict sense), also referred to as **Eumycetes**, are **filamentous, absorptive organisms with chitinous cell walls**, including most species familiar to the general public, such as **Ascomycetes** and **Basidiomycetes**.

**Myxomycetes**, shown in red in *Figure 3.1*, although traditionally studied by **mycologists**, are **not true fungi** and differ significantly from **Eumycetes** in their evolutionary lineage and biological characteristics.

### *1.2 Myxomycetes*

Myxomycetes (unicellular eukaryotes), although sometimes considered fungi, differ from them in two major ways: they feed by phagocytosis rather than absorbotrophy, and they lack mycelium. The plasmodium of Myxomycetes moves in search of food. It is a selective predator of bacteria but also feeds on yeasts, spores, molds, and even small fungi.

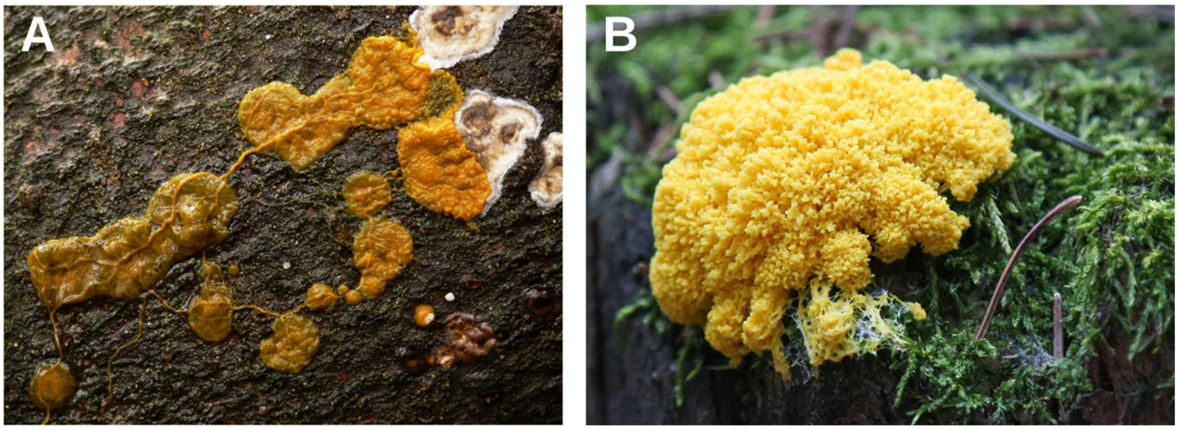



Figure 3.2 - Two examples of Myxomycetes

*A. Plasmodium of Physarum polycephalum (photo by Lebrac, Wikimedia) B. Plasmodium of the scrambled egg slime, Fuligo septica (photo by Maja Dumat, Wikimedia).*

Myxomycetes belong to the group Conosa within the Amoebozoa (Figure 3.1). The term *amoeba* refers to "unicellular animal-like organisms" that produce pseudopodia and change shape as they move. It is sometimes used to describe Myxomycetes, which form gelatinous masses capable of movement. However, this is a polyphyletic group, so the term *amoeba* is no longer used in phylogeny, and most organisms formerly classified as such are now placed in the group Lobosa.

During their life cycle, Myxomycetes go through various morphological stages. Under favorable conditions, they exist in the form of a plasmodium:

- **The plasmodium** is a living structure corresponding to a gigantic single cell filled with multiple nuclei. It is a mass of protoplasm, a hyaline, gelatinous, soft, deformable substance, lacking a rigid cell wall and capable of moving by creeping thanks to the amoeboid motions of its pseudopodia.
- This plasmodial cell forms a gelatinous mass (*Myxomycete* comes from the Greek *muxa*, meaning mucus, slimy, gelatinous, or sticky) that can move in search of food and divides into multiple plasmodia if resources are sufficient (a process known as vegetative multiplication).

Figure 3.3: Different plasmodium

☞ The plasmodium of Myxomycetes has an exceptional survival capacity: if cut, it can instantly reconnect; otherwise, the two parts form independent plasmodia.

In unfavorable conditions, such as drought or freezing temperatures, the plasmodium retracts and retreats into its substrate or forms an almost indestructible sclerotium.

- The *sclerotium* is a hardened, dormant structure formed by the plasmodium itself, allowing it to survive extreme environmental conditions. Unlike fungal sclerotia, which result from the coalescence of hyphae, Myxomycete sclerotia are dehydrated plasmodia that can later reactivate. Some sclerotia develop a membranous outer layer that helps prevent dehydration.

When rehydrated or exposed to moisture, the plasmodium reappears and resumes its search for food. It never revisits the same locations, as it leaves a trail of mucus to mark areas it has already explored.

### *1.2.1 Reproduction of myxomycetes*

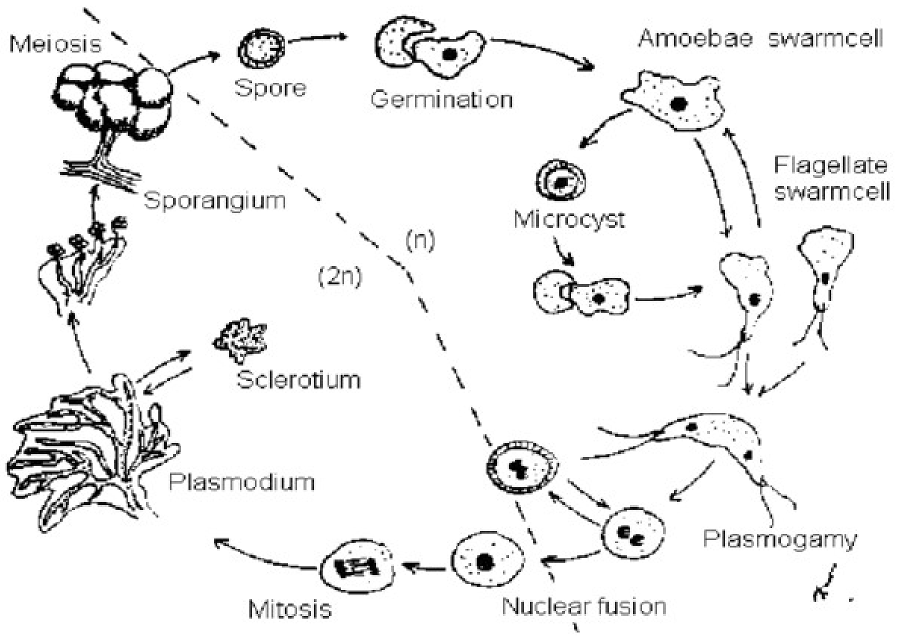



Figure 3.5: Myxomycetes reproduction cycle
(https://www.researchgate.net/publication/326207059_Mycology)

When environmental conditions are favorable—a mystery to us, only the organism knows—after feeding well and growing, the plasmodium begins its reproductive phase by completely transforming into myxocarps, its immobile stage. It undergoes metamorphosis, forming sporocysts that will contain spores for its persistence. This process is very quick; it usually takes only a few hours, often at night. During sporogenesis, a cellulose wall will surround each nucleus to form a spore, and chromosomal reduction will make the spore haploid (n chromosomes).


Figure 3.4: Plasmodium metamorphesis of *Badhamia utricularis*

From the spore, an animal-like cell will emerge, either a myxamoeba or a myxoflagellate, which can move and phagocytize bacteria. There will be several successive mitotic phases, and after some time, two myxamoebas or two myxoflagellates will fuse. Plasmogamy (fusion of cytoplasms) followed by karyogamy (fusion of nuclei) will result in the formation of a cell with a diploid nucleus (2n chromosomes). At this stage, a plasmodium will form, and the nuclei will undergo synchronous mitosis as the plasmodium feeds and grows. The more nuclei the plasmodium has, the more spores it can produce.

### *1.3 Oomycetes*

Oomycetes, or Oomycota, form a distinct phylogenetic lineage of **eukaryotic microorganisms** resembling fungi within the **Heterokonta (Stramenopiles)** (Figure 3.6). Unlike true fungi (**Eumycetes**), their **mycelium is non-septate (coenocytic)**, and their **cell wall contains β-glucans and cellulose**, rather than chitin. This fundamental difference places them closer to **algae** than to fungi in evolutionary terms.

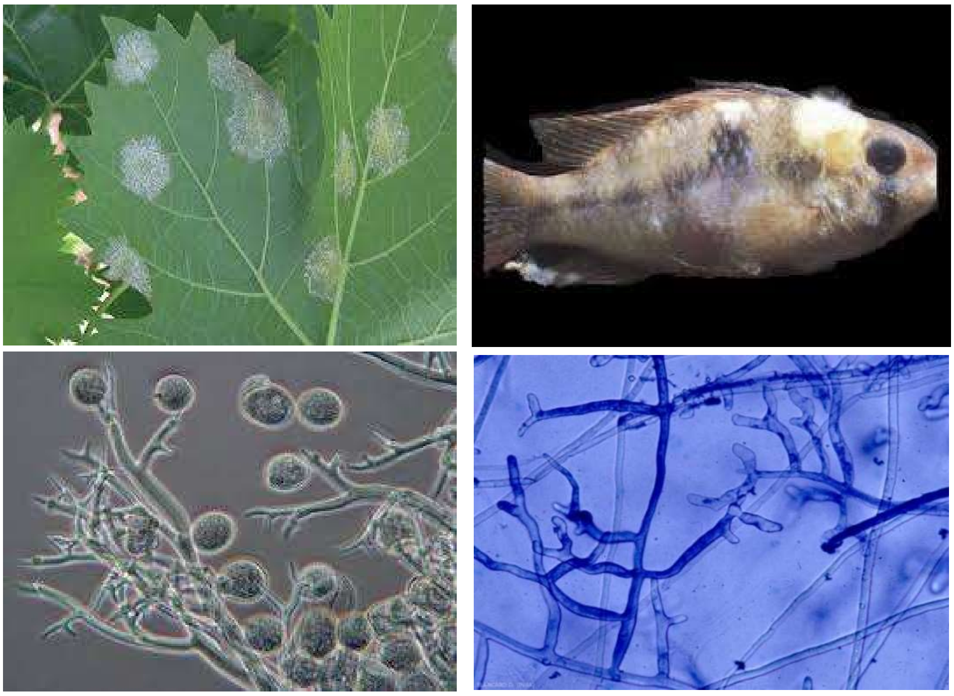


Figure 3.6 : Oomycetes infesting plants and animal (upper pictures) and microscopic coenocytic hyphae (lower pictures)

Oomycetes exhibit both **saprophytic and pathogenic lifestyles**. Some species are among the **most devastating plant pathogens**, causing diseases like **potato late blight** (*Phytophthora infestans*) and **sudden oak death** (*Phytophthora ramorum*).

One of the most infamous **Oomycete-related historical events** was the **Great Irish Famine (1845-1852)**. *Phytophthora infestans* triggered **massive potato crop failures** in Ireland, where potatoes were the primary staple food. This led to **widespread starvation**, causing the deaths of around **one million people** and forcing **another million to emigrate**, primarily to the **United States, Canada, and Australia**.

### *1.3.1 Oomycetes life cycle*

**Asexual reproduction** in Oomycetes primarily occurs through **biflagellate zoospores** (Figure 3.7), produced within **sporangia**. These zoospores have two distinct flagella:

- **Anterior flagellum** (tinsel-type): Covered with tubular hairs, aiding in movement.
- **Posterior flagellum** (whiplash-type): Smooth, used for steering.

This flagella difference is the origin of the term **Heterokonta**, used for Stramenopiles. Depending on the species, flagella may be inserted **apically or laterally**. Zoospores move in water or disperse in soil before encysting, shedding their flagella, and forming a resistant wall for survival.

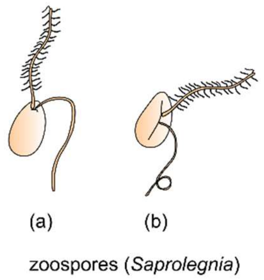



Figure 3.7: *Saprolegnia, stages of asexual reproduction (a) Auxiliary zoospore (b) Principal zoospore According to Webster & Weber, Introduction to Fungi, Cambridge.*

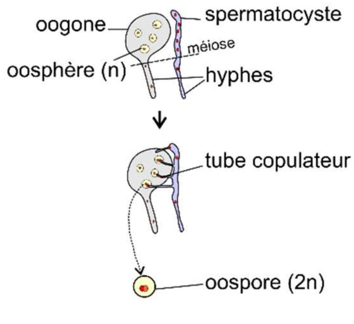
**Sexual reproduction** occurs via **oogamous fertilization**, without zoospores, within specialized structures called **gametangia**:

- **Oogonium (female)**: Produces one or more haploid eggs.
- **Antheridium (male)**: Produces haploid nuclei.

Fertilization involves the **formation of fertilization tubes**, through which the **antheridium delivers its nuclei into the oogonium**. The process includes:

1. **Plasmogamy** (fusion of cytoplasms).
2. **Karyogamy** (fusion of haploid nuclei), forming a **diploid zygote**.

The resulting **oospore** is a thick-walled, resistant structure that ensures survival in harsh environments. This reproductive strategy is known as **oogamy**.




3.8: *Formation of a copulation tube between different types of gametangia and production of*

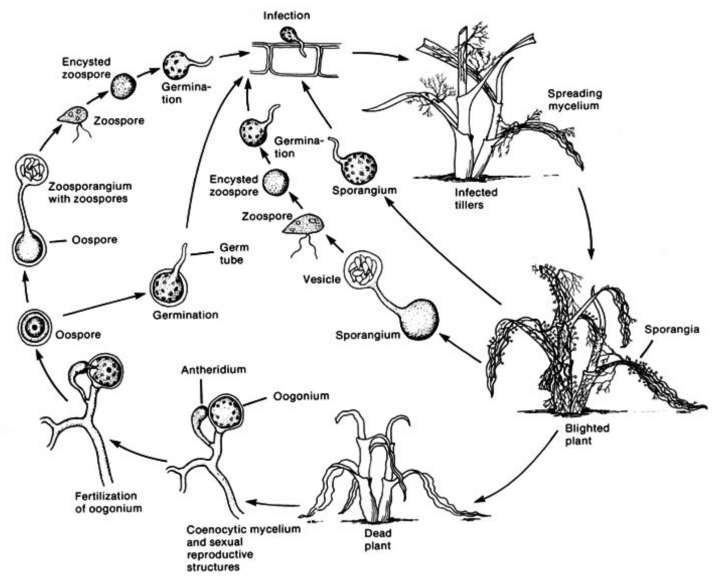



Figure 3.9: *Oomycete life cycle (Adopted from plant clinic-Cornell Education).*

### *1.3.2 Oomycetes as Plant and Animal Pathogens*

Oomycetes are economically significant plant pathogens, with some species also infecting fish (*Saprolegnia* spp.) and mammals (*Pythium insidiosum*, causing pythiosis).

Major Groups of Oomycete Pathogens

a. ***Phytophthora species*** (paraphyletic group)

- Cause late blight (*P. infestans*), sudden oak death (*P. ramorum*), rhododendron root rot, and ink disease in chestnut.
- The Great Irish Famine (1845-1852) resulted from *P. infestans*, devastating potato crops in Ireland and parts of Europe.

b. ***Pythium species*** (paraphyletic group)

- More widespread than Phytophthora, with a broader host range but usually less severe damage.
- Cause damping-off disease in seedlings, particularly in greenhouses.
- Some (*P. oligandrum*) are mycoparasites used as biocontrol agents.

c. ***Downy Mildews*** (obligate biotrophs)

- Appear as white, brown, or olive mildew on leaf undersides.
- Often confused with fungal powdery mildew, but they are unrelated.

d. ***White Blister Rusts*** (Albuginales) (obligate biotrophs)

- Cause white blister disease on flowering plants.
- Form spore-filled blisters under the host epidermis.
- Three main genera:
  - Albugo (on Brassicales, e.g., mustard plants).
  - Pustula (on Asterales, e.g., sunflowers).
  - Wilsoniana (on Caryophyllales, e.g., carnations)

### *1.4 Eumycetes (The true Fungi)*

The **Eumycetes**, or **true fungi**, form a monophyletic clade encompassing most traditional fungi. This term distinguishes them from other fungal-like organisms such as Myxomycetes (slime molds) and certain early-diverging Phycomycetes.

The modern kingdom **Fungi** includes **Microsporidia**, intracellular parasites that were historically classified as protozoa but are now recognized as early-diverging fungi. Together, fungi and animals form the **Opisthokonta** clade (Figure 3.1).

Although around **100,000 fungal species** are formally described, estimates suggest that **2.2 to 3.8 million species** may exist, highlighting the vast diversity of this kingdom.

Fungi are classified based on their **thallus structure** (unicellular, filamentous with or without septa), **mode of sexual reproduction**, and **spore types**. The five major fungal phyla are:

1) **Ascomycota** – The largest group, includes yeasts, molds, and cup fungi.
2) **Basidiomycota** – Includes mushrooms, rusts, and smuts.
3) **Chytridiomycota** – Mostly aquatic fungi with flagellated spores.
4) **Mucoromycota** – (formerly **Zygomycota**, now divided into Mucoromycota and Zoopagomycota).
5) **Glomeromycota** – Arbuscular mycorrhizal fungi that form symbiotic relationships with plant roots.

#### *1.4.1 Ascomycetes*

Ascomycetes belong to the division **Ascomycota**, the largest within the **Fungi kingdom**, with over **64,000 described species**. They are mycelial fungi that produce **endogenous ascospores**. Some species are **unicellular** (such as yeasts), while most form **filamentous hyphae** that develop into a mycelium.

Reproduction occurs in two ways:

- **Asexual reproduction** involves the formation of **exogenous spores** (conidia or conidiospores) on specialized structures called conidiophores.
- **Sexual reproduction** occurs through **endogenous ascospores** produced within a sac-like structure called an **ascus**. Typically, each ascus forms **eight ascospores**, but this number can vary.

Some species have been isolated from **extreme environments**, such as **endolithic fungi** living inside rocks in the icy plains of **Antarctica** and deep-sea fungal species.

The **distinctive characteristic** of this fungal group is the **ascus** (from Ancient Greek ἀσκός *askós*, meaning "sac" or "wineskin"), a microscopic sexual structure where **non-motile ascospores** develop. However, some Ascomycota species reproduce **exclusively asexually** and do not form an ascus or ascospores. These fungi are often referred to as **anamorphic Ascomycetes**. Common examples of Ascomycota include:

- **Morels** (*Morchella* spp.)
- **Truffles** (*Tuber* spp.)
- **Baker's yeast** (*Saccharomyces cerevisiae*)

- **"Dead man's fingers"** (*Xylaria polymorpha*)
- **Cup fungi** (*Peziza* spp.)

☞ ***Systematics***

Ascomycota is a **monophyletic group** (containing all descendants of a common ancestor). Previously classified within **Deuteromycota** alongside asexual species from other fungal taxa, **asexual (or anamorphic) Ascomycetes** are now identified and classified based on **morphological or physiological similarities** with ascus-bearing taxa, as well as **phylogenetic analyses of DNA sequences**.

☞ ***Ecology***

Ascomycetes are of particular importance to humans as sources of **medicinal compounds**, such as **antibiotics**, and for their role in the **fermentation of bread, alcoholic beverages, and cheese**. Examples include **Penicillium species**, which are involved in cheese production and in the synthesis of antibiotics like **penicillin** (*Penicillium chrysogenum*). Other Ascomycetes produce medically significant compounds, such as **lovastatin** (a cholesterol-lowering drug from *Aspergillus terreus*) and **cyclosporine** (an immunosuppressant from *Tolypocladium inflatum*).

Many Ascomycetes are **pathogens** that affect **animals, humans, and plants**:

- **Human-infecting Ascomycetes** include *Candida albicans*, which causes **candidiasis**, and *Aspergillus niger*, which can cause **aspergillosis** in immunocompromised individuals. Additionally, several **dermatophytes** (*Trichophyton*, *Microsporum*) cause **skin infections** such as ringworm.
- **Plant pathogens** include *Venturia inaequalis* (causing **apple scab**), *Magnaporthe oryzae* (**rice blast**), *Claviceps purpurea* (**ergot fungi**, which produce toxic alkaloids in grains), *Apiosporina morbosa* (**black knot**), and **powdery mildew** fungi from the order **Erysiphales**.

Some Ascomycetes are **entomopathogenic**, meaning they **parasitize and kill insects**. Members of the genus **Cordyceps** (e.g., *Ophiocordyceps unilateralis*) infect insects, while **Beauveria bassiana** has been successfully used in **biological pest control**.

Several Ascomycete species serve as **model organisms** in laboratory research. The most well-known include:

- *Neurospora crassa*, a key model for **fungal genetics and circadian rhythm studies**.
- **Yeast species**, such as *Saccharomyces cerevisiae* and *Schizosaccharomyces pombe*, which are essential in **genetics and molecular biology**.
- *Aspergillus nidulans*, widely used in **cell cycle and secondary metabolism studies**.

#### *1.4.1.1 Ascomycetes reproduction*

The reproduction of Ascomycetes involves highly variable mechanisms depending on the species. It can be **sexual or asexual**.

☞ ***Sexual multiplication***

Les The hyphae are **septate** (with septa separating the cells).

The life cycle is **haplontic** (haploid-dominant) and alternates between three main stages:

1. **A haploid monokaryotic phase** begins when ascospores germinate and form **haploid mycelia** with a single nucleus per cell. These mycelia are of different **mating types (+ and -)**.
2. **Plasmogamy occurs** when compatible mating types fuse, leading to a **dikaryotic phase** (cells contain two separate nuclei).
3. **Karyogamy (nuclear fusion)** takes place in a specialized cell, forming a **diploid zygote**, which **immediately undergoes meiosis** within a protective structure called an **ascus**, producing **four haploid nuclei**.
4. **Each of the four nuclei undergoes mitosis**, resulting in **eight haploid ascospores**.
5. **The mature ascus ruptures**, releasing its **ascospores**, which germinate into **haploid monokaryotic hyphae**, restarting the cycle.

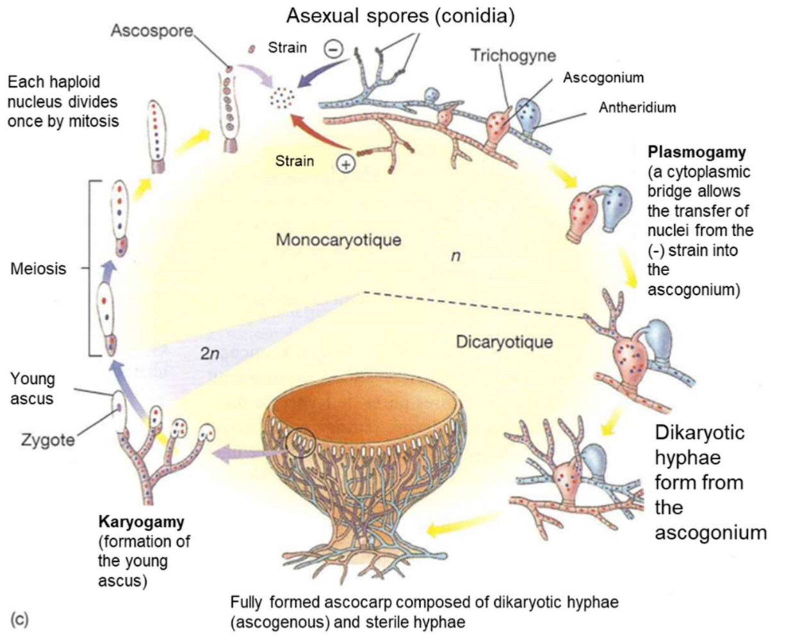
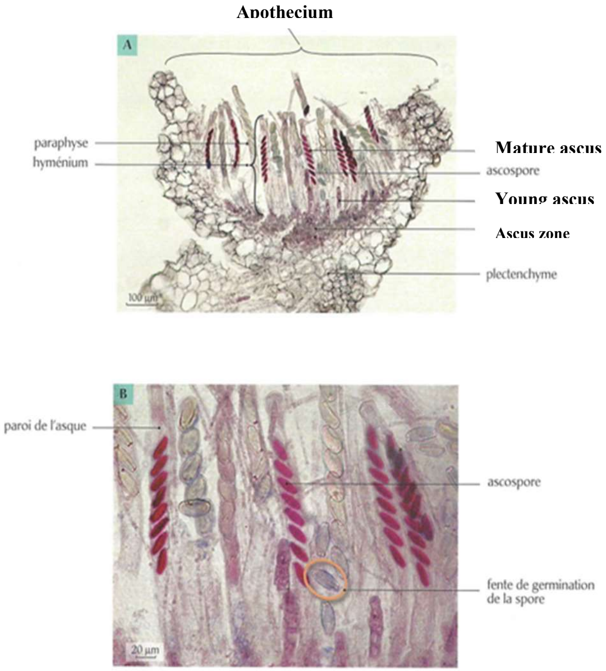
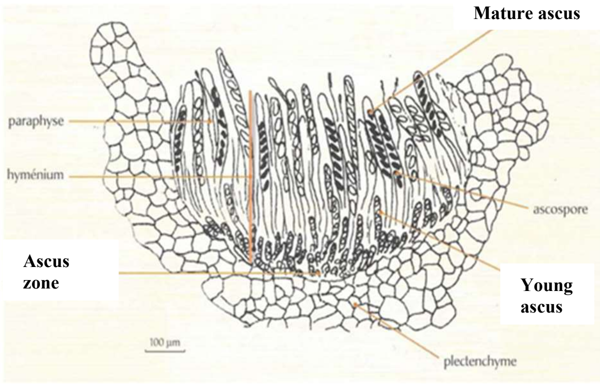



Figure 3.10: Reproduction cycle of ascomycete.

Locally, multinucleated structures (**gametocysts**) are formed. The **"female" gametocyst** (**+ strain**) produces small hair-like structures (**trichogynes**) that enable fusion with the **"male" gametocyst** (**- strain**), allowing the migration of **- nuclei** into the **+ gametocyst**.

- **A haploid dikaryotic phase**: The cells remain haploid but contain **two genetically distinct nuclei per cell** (**dikaryotic state**). During this phase, **septate, binucleate hyphae** develop, giving rise to the fruiting body known as the **ascocarp**. There are two main types of ascocarps:
    - **Perithecium**: Flask-shaped
    - **Apothecium**: Broad, cup-shaped (see figure).
- **A diploid phase restricted to the zygote**: The zygote forms within the **ascus** through **karyogamy** (fusion of the two nuclei). This **diploid phase** is transient and limited to the zygote, as **meiosis occurs immediately**, restoring the **haploid state** and leading to the formation of ascospores




Observation drawing of a **longitudinal section** of a **Peziza apothecium** viewed under a **light microscope.**

Figure 3.12 ***(Images from Wikipedia):***
***Bulgaria inquinans*** *ascocarp in* ***apothecium*** *form (right).*
***Morchella conica*** *ascocarp in* ***perithecium*** *form (left).*

Figure 3.11: Apothecium. After BOUTIN et al. (2010)

☞ ***Asexual (or vegetative) reproduction*** is **predominant in Ascomycetes** and is responsible for their rapid expansion. It occurs through **conidiospores** or **conidia** (see figure), which originate from the budding of **more or less specialized cells**, called **conidiogenous cells**. **Conidiogenous cells** are usually grouped at the tips of stalk-like structures called **conidiophores**, which facilitate the **dispersal of conidia** by wind, water, or animals. This allows Ascomycetes to **rapidly colonize new environments** and survive under **unfavorable conditions**. Some conidia exhibit **resistance to desiccation, UV radiation, or extreme temperatures**, making them highly adaptable for long-distance dispersal. The formation of conidia varies among species; they can develop **singly or in chains**, depending on the fungal species. For example, **Penicillium** and **Aspergillus** produce vast numbers of conidia, contributing to their **ecological role and industrial applications** (e.g., antibiotic production and food fermentation). While **asexual reproduction dominates**, some Ascomycetes switch to **sexual reproduction** under **stress or changing environmental conditions**, ensuring **genetic recombination and adaptation**. This balance between **rapid clonal expansion and genetic diversity** allows Ascomycetes to thrive in diverse habitats.

### *1.1.1 Biology of Lichens (part of ascomycetes)*

Lichens are highly successful self-supporting associations between a fungus (the fungal partner, the "mycobiont") and one or more green algae or cyanobacteria (the photosynthetic partner, the "photobiont"), along with other microscopic organisms (mainly bacteria). They form a mutually beneficial, stable, and ecologically obligatory symbiosis, where the fungal partner creates the external structure (the "exhabitant") and surrounds but does not penetrate the included photosynthetic partners, specialized non-photosynthetic bacteria, and sometimes other fungi. They are often considered ecosystems rather than individual organisms.

☞ ***Symbiosis and Partners***

- **Mycobiont (fungal partner)**: Usually an Ascomycete (sometimes a Basidiomycete). Provides structure and absorbs water.
- **Photobiont (photosynthetic partner)**: Green algae (e.g., *Trebouxia*, *Trentepohlia*) or cyanobacteria (*Nostoc*). Produces carbohydrates via photosynthesis.
- **Bacterial microbiome**: Some lichens harbor bacteria that aid in nitrogen fixation or secondary metabolism.

☞ ***Morphology and Structure figure 3.13a , 3.13b***

Thallus types: Crustose (crust-like), Foliose (leaf-like), Fruticose (shrub-like), Squamulose (scale-like).

Anatomy: Different layers in the thallus—upper cortex, algal layer, medulla, lower cortex, and rhizines for attachment.

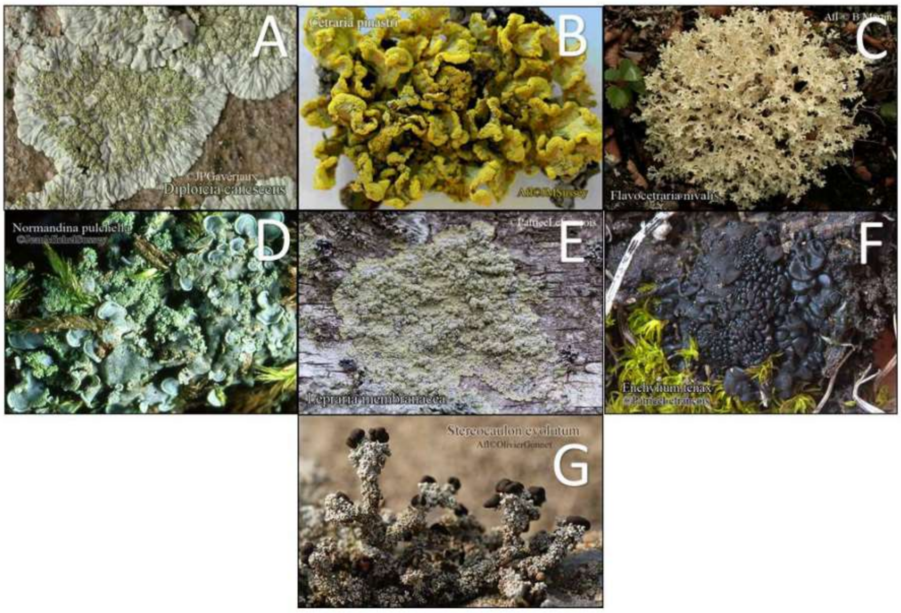



Figure 3.13a: **Illustration of the main morphological types of lichens:**
a – Crustose thallus of *Diploicia canescens*
b – Foliose thallus of *Vulpicida pinastri*
c – Fruticose thallus of *Flavocetraria nivalis*
d – Squamulose thallus of *Normandina pulchella*
e – Leprose thallus of *Lepraria membranacea*
f – Gelatinous thallus of *Enchylium tenax*
g – Complex thallus of *Stereocaulon evolutum*

(Image: Pierre Le Pogam-Alluard, 2016, *Analysis of lichens by mass spectrometry: dereplication and histolocalization*).

### ☞ *Ecology*

Lichens play an important role in the nutrient cycle and act as producers that serve as food for many higher trophic consumers, such as animals, gastropods, nematodes, mites, and springtails. Lichens have properties different from those of their constituent organisms. They come in various colors, sizes, and shapes and sometimes resemble plants, but they are not plants. They can have small, leafless branches (*fruticose*), flat, leaf-like structures (*foliose*), grow in a crust-like form, tightly adhering to a surface (substrate) like a thick layer of paint (*crustose*), have a powdery appearance (*leprose*), or exhibit other growth forms.

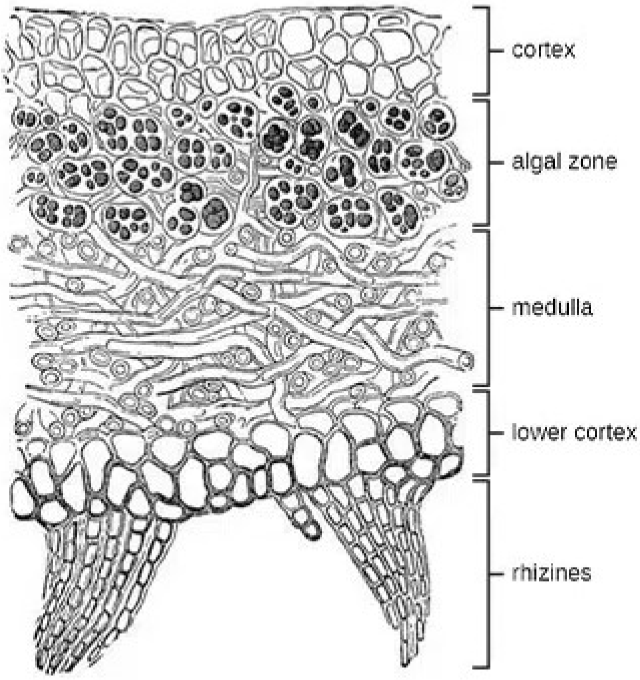



Figure 3.13b: lichen structure lichen diagram

Lichens inhabit diverse environments, from sea level to alpine altitudes, growing on various surfaces like tree bark, leaves, mosses, rocks, walls, and even within solid rock (endolithic). They thrive in extreme conditions, including Arctic tundras, deserts, and coastal areas. Covering an estimated 6–8% of Earth's land surface, around 20,000 species are known. Some have lost the ability to reproduce sexually but continue to specialize.

Lichens function as self-sustaining miniature ecosystems, where fungi, algae, or cyanobacteria interact with other microorganisms. They are among the longest-living organisms, with some used for dating geological events (lichenometry). As pioneer species, they colonize fresh rock surfaces after disturbances and play crucial roles in ecosystems, benefiting trees and birds.

### ☞ *Reproduction of lichen*

Similar to Ascomycetes, lichens reproduce through vegetative, asexual, and sexual modes.

- **Vegetative reproduction** occurs by simple thallus fragmentation (budding) or specialized structures:
  • *Isidia* – small outgrowths containing both symbionts
  • *Soralium* – thallus fissures releasing *soredia* (clusters of algal cells surrounded by fungal hyphae)
  • *Soredia* – formed without soralia
  • *Pycnidia* – spore-producing structures
- **Asexual reproduction** is carried out solely by the fungal partner (*mycobiont*), producing *conidia* at hyphal tips embedded in the thallus.
- **Sexual reproduction** also involves the mycobiont, forming specialized structures:
  • *Apothecia* – cup-shaped fruiting bodies on the thallus surface
  • *Perithecia* – flask-shaped structures embedded in the thallus

Spores are released via specific mechanisms, including osmotic pressure buildup, leading to explosive ejection. These reproductive structures are key traits for species identification.

### *1.1.2 Basidiomycetes*

☞ ***Biology***

**Basidiomycota** is one of the two major divisions of the **subkingdom Dikarya** (often referred to as the "higher fungi") within the **kingdom Fungi**, alongside **Ascomycota**. Members of this division are known as **basidiomycetes**. Basidiomycota includes various groups such as **agarics (gilled mushrooms), puffballs, stinkhorns, bracket fungi, other polypores, jelly fungi, boletes, chanterelles, earth stars, smuts, bunts, rusts, mirror yeasts, and Cryptococcus**, a pathogenic yeast affecting humans.

Basidiomycetes play **key ecological roles** as decomposers, mutualists (e.g., mycorrhizal fungi associated with plant roots), and pathogens. Many forms **symbiotic relationships with plants**, aiding in nutrient uptake, while others, such as **rusts and smuts**, are major agricultural pathogens.

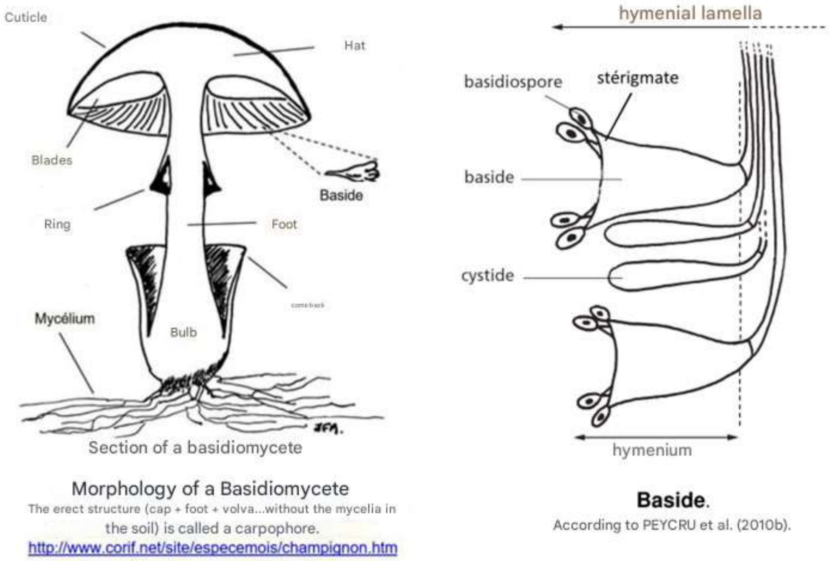



Figure 3.14a: Organization of a Basidiomycete. After PEYCRU et al. (2010)

They are **filamentous fungi** composed of **septate hyphae** (except for basidiomycete yeasts) and reproduce **sexually** via **basidia**, which are **club-shaped** terminal cells bearing **externally produced meiospores** called **basidiospores** (typically four per basidium) (Fig. 3.14). Some **Basidiomycota**, however, reproduce **asexually** and lack sexual structures.

Basidiomycota that reproduces asexually are often **identified based on morphological features** such as **clamp connections** (a characteristic of septate hyphae), **specific cell wall components**, and **phylogenetic analysis of DNA sequences**. Unlike Ascomycota, where spores form internally within **asci**, Basidiomycota uniquely produce spores externally on the basidium.

Basidiomycetes are also notable for their **complex life cycles**, often involving **long-lived dikaryotic (n+n) mycelia** before karyogamy (nuclear fusion) occurs, followed by meiosis to produce haploid spores. Many species form **large fruiting bodies** (basidiocarps), such as mushrooms, while others exist as **microscopic plant pathogens** or **yeasts**

## ☞ *Ecology*

Basidiomycota are generally **low-competitive organisms**, often occupying **specialized ecological niches** such as **parasitism, symbiosis, or lignivory**. These lifestyles allow them to exploit **substrates where competition with Ascomycota (including their imperfect forms) and bacteria is limited**.

Parasitism is particularly common among **Basidiomycota that do not produce large, aggregated basidiocarps**, such as **rust fungi (Pucciniales, formerly Urédinales), smut fungi (Ustilaginales), and Exobasidiales**. These groups often have **complex life cycles involving obligate parasitism** on plants. In contrast, other basidiomycetes are **mainly saprotrophic or symbiotic**, playing key roles in nutrient cycling and ecosystem stability.


Figure 3.14b: Examples of Basidiomycota diversity. Pucciniomycotina: (a) uredinia of *Puccinia iridis*; (b) fruiting body of *Phleogena faginea*; (c) aecia of Coleosporium; (d) yeast state of *Symmetrospora oryzicola*. Ustilaginomycotina: (e) smut galls of *Ustilago maydis*; (f) gall of Exobasidium; (g) culture of *Moniliella* sp. Agaricomycotina: (h) culture of Wallemia; (i) stinkhorn fruiting body of Phallus (photo by Nu Nguyen). (j) coral fruiting body of Clavaria; (k) crust fruiting body of Amylostereum; (l) club fruiting body of Clavariadelphis; (m) polypore, conk fruiting body of Pycnoporus; (n) gilled mushroom fruiting body of Russula; (o) pored mushroom fruiting body of Boletus; (p) puffball fruiting body of Lycoperdon.

### o *Lignivorous Basidiomycota: Decomposers of Wood*

Lignivorous basidiomycetes, despite sometimes growing on **living trees**, are fundamentally **saprotrophic**—they primarily degrade **dead tissues** such as **heartwood** rather than actively harming living plant cells. Their activity is **essential for forest ecosystems**, as they are among the **few organisms capable of breaking down lignin**, a complex polymer found in plant cell walls.

Some **lignivorous species** specialize in **white rot**, where they degrade both lignin and cellulose, leaving behind a pale, fibrous material. Others cause **brown rot**, where lignin is largely left intact, and cellulose is selectively broken down, leading to a cuboidal, brittle decay. These fungi play a **crucial role in the carbon cycle**, facilitating the return of organic matter to the soil.

### o *Basidiomycetes and Early Stages of Plant Debris Decomposition*

Unlike most **bacteria and Ascomycota**, which primarily act on already decomposed organic matter, **Basidiomycota initiate the first stages of lignocellulosic degradation**. This allows them to colonize **nutrient-rich, undecomposed plant debris**, making them **primary decomposers** in many ecosystems.

Their enzymatic capabilities—especially **laccases, peroxidases, and hydrolases**—enable them to break down **tough plant materials** that other microbes cannot. This makes them valuable not only in **natural ecosystems** but also in **biotechnology applications**, such as **bioremediation, biofuel production, and waste decomposition**.

☞ ***Basidiomycetes Reproduction***

o ***<u>Sexual reproduction</u>***

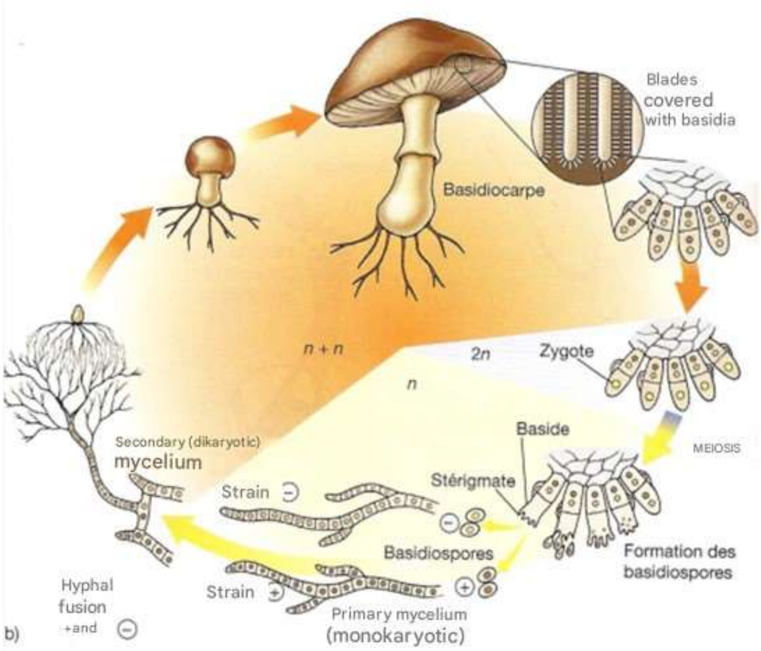



Figure 3.15: Reproduction cycle of a Basidiomycete. After RAVEN et al. (2007).

***Haploid Thalli & Primary Mycelium***

o Two haploid thalli (+ and –) form monokaryotic hyphae, creating a primary mycelium.

***Plasmogamy & Secondary Mycelium***

o Fusion of cytoplasm (plasmogamy) occurs between (+ and –) hyphae, forming a dikaryotic (n + n) secondary mycelium, which dominates the life cycle.

***Fruiting Body & Spore Formation***

The basidiocarp (mushroom) develops, with basidia on gills or pores.

o Inside basidia, karyogamy (nuclear fusion) → diploid zygote → meiosis → four haploid basidiospores.

***Spore Release & Germination***

o Basidiospores disperse, germinate, and form new primary mycelia, restarting the cycle.

- ***<u>Asexual reproduction</u>***

o **Conidia Formation:**
- Asexual spores (conidia) are rare in Basidiomycota compared to Ascomycota.
- Some Basidiomycetes can reproduce asexually via conidia, but most rely on **fragmentation of hyphae or budding (**fig 3.16) (in yeasts).

o **Role of Asexual Reproduction:**

- Asexual reproduction is **less common** and plays a **secondary role** compared to sexual reproduction in Basidiomycota.
- Many Basidiomycetes **lack** a well-developed asexual phase.

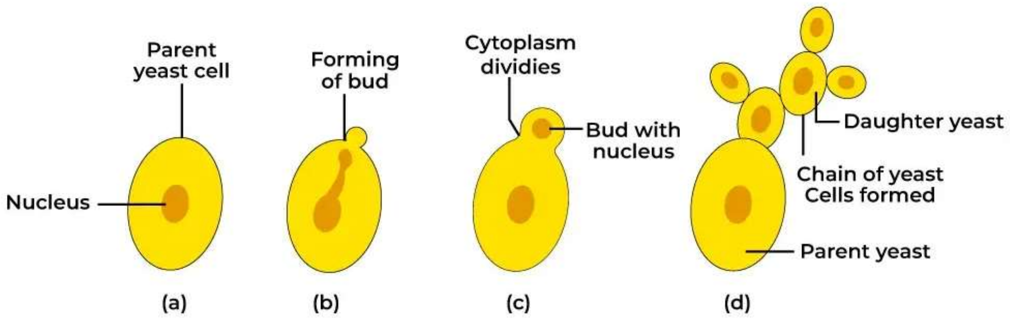



Figure 3.16: Budding in yeast

### *1.1.3 Glomeromycota (Endomycorrhizal Fungi)*

☞ ***Biology***

Glomeromycota, often referred to as **glomeromycetes**, is a division of fungi that includes a single class, **Glomeromycetes**. These fungi are **exclusively endomycorrhizal**, forming symbiotic associations with the roots of a wide range of plants.

Previously classified within the order **Glomales** under the **Zygomycota**, they were later recognized as a distinct group. To date, approximately **230 species** have been described.

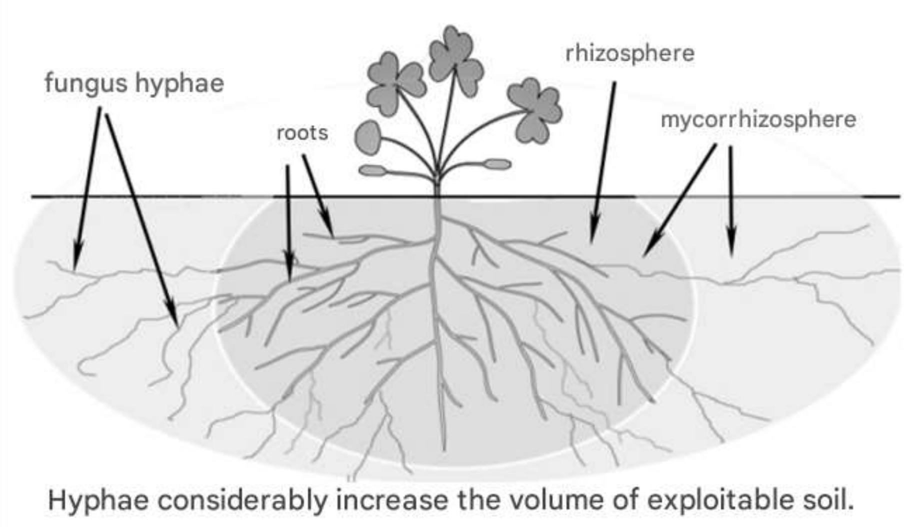



Figure 3.16: Importance of glomeromycota for plants

☞ ***Role of Glomeromycota in Plant Nutrition***

Glomeromycota help **over 80% of herbaceous plants** and **many tropical trees** absorb **water and mineral nutrients**, especially **phosphorus**, from the soil. They achieve this through a specialized type of mycorrhiza known as **vesicular-arbuscular mycorrhizae (VAM)** or **arbuscular mycorrhizae (AM)**.

Unlike **ectomycorrhizae**, which are formed by fungi such as lactarius, russulas, boletes, and cortinarius in **temperate and Arctic Forest ecosystems**, VAM fungi penetrate **root cells**, forming **vesicles and arbuscules** to enhance nutrient exchange.

☞ ***Systematic***

Recent phylogenetic studies led to the establishment of **Glomeromycota** as a distinct, monophyletic phylum within the **Mucoromycota subkingdom**, separating them from the former Zygomycota classification. These fungi form **obligate symbiotic relationships** with plant roots, facilitating water and mineral nutrient uptake, particularly phosphorus, through **vesicular-arbuscular mycorrhizae (VAM)**. More than **80% of herbaceous plants and many tropical trees** depend on these fungi for efficient nutrient acquisition.

A unique exception within this group is **Geosiphon pyriforme**, which does not associate with plants but forms a symbiosis with **cyanobacteria (*Nostoc*)**, making it the only known Glomeromycota species engaged in a **prokaryotic photosynthetic partnership**.

Currently, Glomeromycota is divided into **four orders**:

1. **Glomerales** (formerly Glomales)
2. **Diversisporales**
3. **Paraglomerales**
4. **Archaeosporales** (formerly Geosiphonales)

The family **Geosiphonaceae**, within Archaeosporales, is monotypic, containing only **Geosiphon pyriforme**, which was once considered a lichenized species.

Unlike most fungi, **Glomeromycota lack sexual reproduction** and propagate exclusively through **large, multinucleate asexual spores (glomerospores)**. Their ability to **colonize plant roots is essential for their survival**, making them **strictly dependent on their host plants**. They play a crucial role in ecosystems by enhancing plant growth, improving soil structure, and facilitating nutrient cycling.

☞ ***Life cycle of glomeromycota***
***a) Development of Hyphae in the Soil***

Les Hyphae in Glomeromycota originate from **two main sources**:

1. **Spore germination** – These hyphae have a short lifespan and will die if they do not quickly find a compatible root, as these fungi are **obligate biotrophs** and cannot grow without a host.
2. **Pre-existing mycorrhizal roots** – These hyphae develop from previous mycorrhizal associations, expanding the **mycelial network** to absorb nutrients or colonize new roots.

Glomeromycota hyphae are **coenocytic** (non-septate), meaning their nuclei share a common cytoplasm. Based on function, **four types of extraradical hyphae** are distinguished:

- **Absorptive hyphae** – Thin, highly branched filaments specialized in nutrient uptake.
- **Conductor hyphae** – Thicker hyphae with sparse cytoplasm, involved in nutrient transport.
- **Infectious hyphae** – Responsible for colonizing new roots.
- **Sporogenous hyphae** – Produce spores for fungal propagation.

.

### *b) Root-Hyphae Interaction and Colonization*

As a root grows and encounters soil hyphae—either newly germinated or in a dormant state due to reduced metabolic activity—the hyphae are **chemically attracted** to the root. They align along its surface, establishing contact points where **small swellings, called appressoria**, form. These structures facilitate fungal penetration into the root's outer layers by moving **between epidermal and cortical cells**.

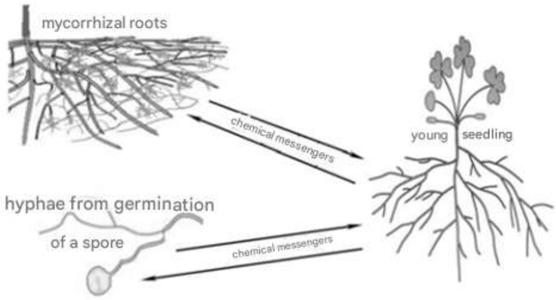



Figure 3.17: Interaction with the root of a plant (Based on a diagram found on the website: http://mycorrhizas.info/resource.html#photos)

This communication between the hypha and the root is facilitated by the release of chemical substances by the plant, the most common being strigolactone molecules (such as 5-deoxy-strigol), which stimulate the activity of the fungus's mitochondria, thereby reactivating its metabolic functions.

### *a) Intraradical Proliferation and Arbuscule Formation*

When the appressorium forms, the hypha advances through intercellular spaces using two propagation modes: **linear movement along longitudinal spaces** and **coiling when space is restricted**. After a few days, the hyphae branch into finer structures, forming **arbuscules**—tree-like structures that penetrate plant cells without entering their cytoplasm. This increases contact between the fungus and the plant, **enhancing nutrient exchange**. *Arbuscules are short-lived but can persist under certain conditions before being absorbed by the root cell, providing the plant with essential nutrients*.

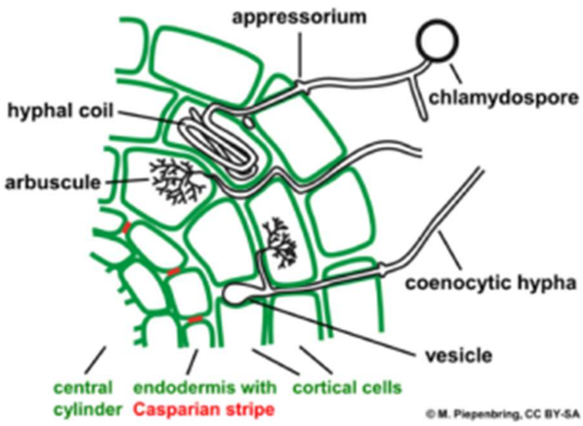



Figure 3.18: Proliferation of Hyphae, Formation of Arbuscules and Vesicles (Figure by M. Piepenbring site : http://mycorrhizas.info/resource.html#photos)

### *b) Vesicle Formation*

After arbuscule development, some hyphae swell to form **vesicles**, which store lipids and triacylglycerols (TAG). These vesicles, which can be inter- or intracellular, act as nutrient reservoirs. In older root cortex cells, vesicle walls may thicken, though they are absent in the **Gigasporinae** group.

#### *c) Reproduction*

Genetic studies using molecular markers have not detected recombination, suggesting these fungi lack sexual reproduction. Instead, they propagate via **asexual spores (mitospores)**. These mitospores form when the symbiotic relationship weakens or when the fungus utilizes stored nutrients.

*Specific sporogenic hyphae develop swollen structures filled with cytoplasm, nuclei, and reserves, which mature into thick-walled mitosporangia.* Mitospores can be **free or grouped into mitosporomes**, serving as both dispersal units and long-term storage structures. Some mitospores contain microorganisms whose role in the rhizosphere remains unclear.

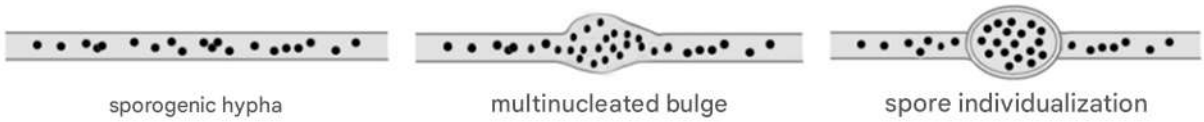



Figure 3.19: Asexual spores' formation

☞ ***Symbiotic Benefits***

- The **mycorrhizal fungus depends on the plant** for carbohydrates, mainly glucose, which it uses for energy, structure building, and storage.
- The **plant benefits** by expanding its soil exploitation capacity, forming a **mycorrhizosphere** that enhances nutrient and water uptake.
- This **mutualistic interaction** is particularly advantageous in harsh environments, such as deserts, where fungal hyphae can access deep water sources.

### *1.1.4 Mucoromycota*

Mucoromycotes represents a distinct evolutionary lineage within the fungi formerly grouped as zygomycetes, characterized by specific morphological traits, diverse ecological roles, and a revised taxonomic framework that reflects their true evolutionary relationships.

Mucoromycotes is one of the two major groups that emerged from the reclassification of the traditional Zygomycota based on molecular phylogenetic studies. Here are some key points about Mucoromycotes:

- **Taxonomic Revision**: Formerly, many fungi were lumped together under Zygomycota. However, molecular data revealed that this group was polyphyletic, leading to its division into two main lineages: **Mucoromycota** and **Zoopagomycota**.

- **Morphological and Reproductive Characteristics**: Members of Mucoromycota typically have coenocytic (aseptate) or sparsely septate hyphae. They reproduce both sexually (by forming zygospores through cystogamy) and asexually (often via sporangiospores). These features are consistent with the classical characteristics originally associated with the zygomycetes.

- **Ecological Roles**: Many species within Mucoromycota are saprotrophs, playing an essential role in the decomposition of organic matter in soil. Some species also engage in symbiotic relationships with plants, such as forming mycorrhizal associations, while others can be opportunistic pathogens affecting plants, animals, or even humans.

- **Diversity and Distribution**: With a significant number of species, the fungi within Mucoromycota are primarily terrestrial, thriving in soils and on decomposing organic materials. Their rapid growth and prolific asexual reproduction enable them to colonize diverse environments quickly.
- **Ongoing Research**: Taxonomic classifications within these groups are still evolving as new molecular and genomic data become available. As a result, the precise boundaries and relationships among various orders within Mucoromycota continue to be refined.

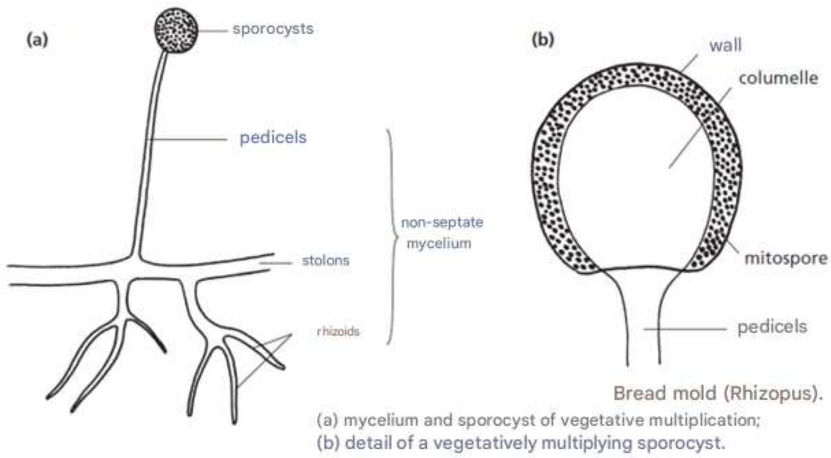



Figure 3.20: Vegetative apparatus of a Mucorale. According to Peycru et al. (2010).

☞ ***Ecology***

Approximately 1,060 species of Mucoromycota are known. They are primarily terrestrial, inhabiting soil or growing on decomposing plant or animal matter. Many of these fungi are saprotrophs that play a crucial role in breaking down dead organic material. Some species act as parasites of plants, insects, and small animals, while others form beneficial symbiotic relationships with plants—most notably in mycorrhizal associations.

Members of Mucoromycota typically have non-septate (coenocytic) or sparsely septate hyphae and reproduce both sexually (via the formation of zygospores through cystogamy) and asexually (often by producing sporangiospores). Their rapid growth and prolific asexual reproduction enable them to quickly colonize available substrates in their environment.

Molecular phylogenetic studies have demonstrated that the traditional Zygomycetes were polyphyletic, leading to a reclassification in which species once grouped together are now divided into two distinct groups—Mucoromycota and Zoopagomycota—reflecting their separate evolutionary histories.

☞ ***Reproduction within Mucoromycetes***

***Asexual Reproduction***

- The primary mode of reproduction in Mucoromycota is **asexual** via the production of **sporangiospores**.
- These spores are formed inside specialized **sporangia**, which develop on stalk-like structures called **sporangiophores**.

- When mature, the sporangia release thousands of spores, which germinate into new fungal colonies under favorable conditions.

***Sexual Reproduction***

- **Haploid Thalli and Mating Types** : Two haploid thalli (designated as + and –) exist. These thalli, which are non-septate (coenocytic) hyphae, are attracted to each other.
- **Formation of Gametocysts and Gametes**: Upon meeting, they produce gametocysts within which gametes are generated.
- **Cystogamy and Zygosporocyst Formation**: The gametocysts from the + and – types fuse (a process called cystogamy) to form a coenozygocyst (or zygosporocyst). Here, nuclei fuse pairwise (karyogamy), but typically only one diploid nucleus persists.
- **Immediate Meiosis**: This diploid nucleus then undergoes immediate meiosis, resulting in a rapid return to the haploid state (making the cycle predominantly haploid, or haplophasic). Only one of the haploid nuclei remains, becoming a meiospore.
- **Germination and Asexual Reproduction**: The meiospore germinates and produces a zygosporocyst that contains zygospores formed by mitosis. These zygospores then germinate to produce the vegetative hyphae (the mold), which can further reproduce vegetatively by forming mitospores.

While this description accurately reflects the classical sexual reproduction cycle in many Mucoromycota, it's important to remember that some species may show variations in their reproductive processes.

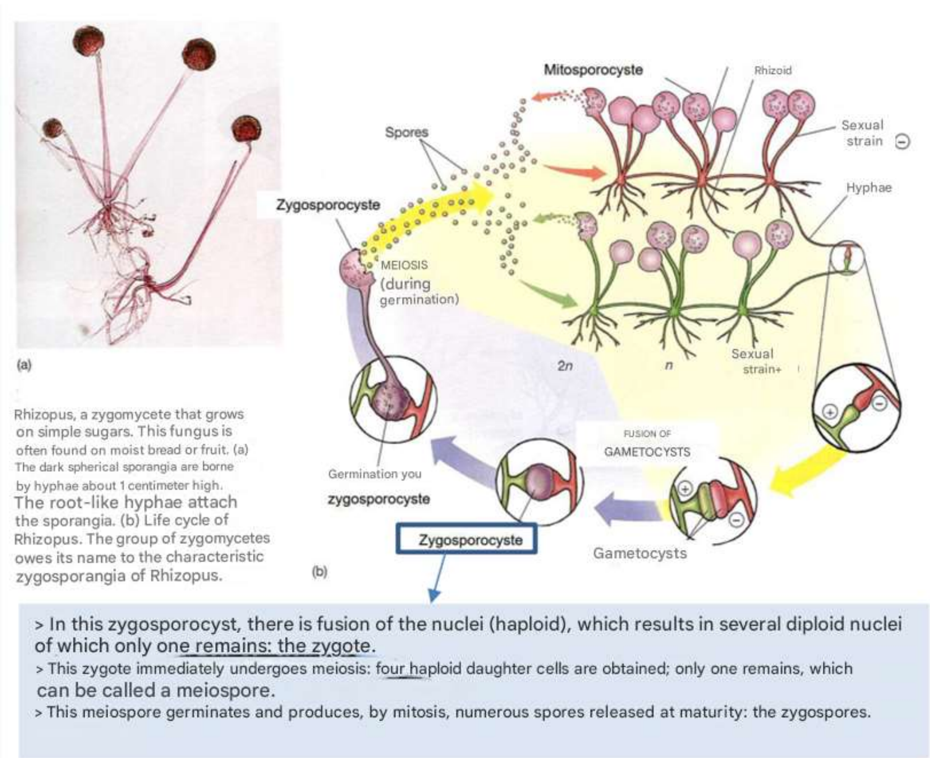



Figure 3.21: Reproduction cycle of Mucorales. After RAVEN et al. (2007).

### *1.1.4.1 Zoopagomycota*

- **Taxonomy**: Formerly placed in the polyphyletic Zygomycota, Zoopagomycotina is now recognized as a subphylum within the phylum Zoopagomycota.
- **Lifestyle**: These microscopic fungi are typically obligate parasites of other fungi and small soil organisms (e.g., nematodes, rotifers, amoebae), using haustoria to extract nutrients.
- **Morphology**: They feature coenocytic (non-septate) hyphae with chitinous cell walls.
- **Reproduction**: They reproduce asexually via various spores (arthrospores, chlamydospores, sporangiola, merosporangia) and sexually by forming globose zygospores in structures historically called zygosporangia.

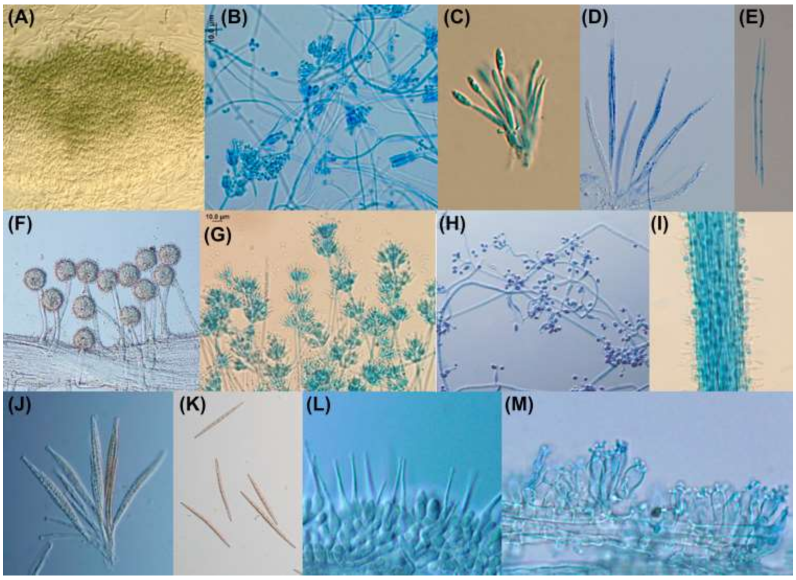



Figure 3.21b: Some microscopic Zoopagomycetes

### *1.1.5 Chytridiomycota*

Chytridiomycetes, also known as chytrids, are a group of microscopic fungi that belong to the phylum Chytridiomycota. They display several ancestral characteristics, including the production of motile, uniflagellate zoospores that play a crucial role in their dispersal. This group is considered among the earliest fungi, with some of the oldest fungal fossils attributed to chytrids, underscoring their evolutionary significance.

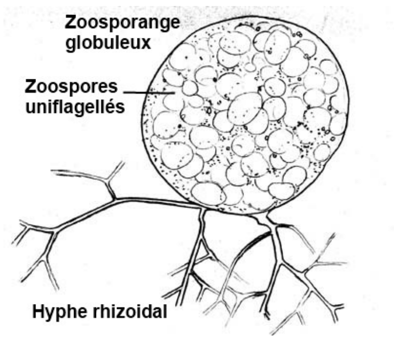



Figure 3.22: Chytridiomycete structure, *Chytridium confervae* (https://www.researchgate.net/publication/281035050_978-3-8417-9776-6)

- ***Ecology***

These fungi are predominantly aquatic, thriving in freshwater, marine environments, and damp terrestrial areas such as soils and swamps. They are also found in specialized habitats, including the digestive tracts of certain animals. Chytridiomycetes exhibit a versatile lifestyle; many are saprophytic, contributing to the breakdown of complex organic matter, while others are parasitic. Notably, some chytrids infect algae, plants, and amphibians—with some species being responsible for chytridiomycosis in amphibians—highlighting their ecological impact.

☞ ***Morphology***

The life cycle of Chytridiomycete is marked by the production of motile zoospores, which, upon settling, encyst and develop into a thallus. The thallus can be unicellular or develop into more complex multicellular or coenocytic structures. In many species, specialized rhizoids form, aiding in nutrient absorption and anchoring the fungus to its substrate. This combination of motile zoospores and a diverse thallus structure allows chytridiomycetes to efficiently colonize their environments and adapt to various ecological niches.

Overall, the ancestral features, ecological diversity, and unique reproductive strategies of chytridiomycetes make them a key group for understanding fungal evolution and their roles in both aquatic and terrestrial ecosystems.

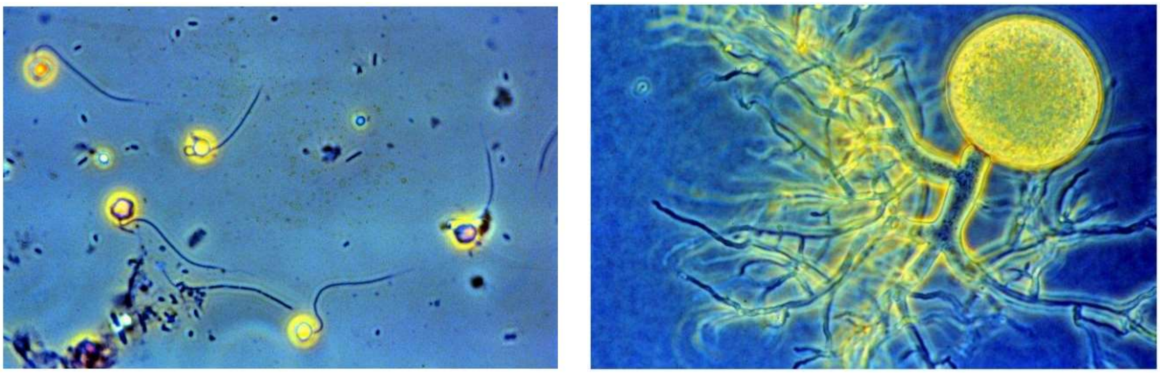


Figure 3.23: Structure of a Chytridiomycete, Microscopic Observation (Uniflagellate Zoospores on the Left; Rhizomycelium on the Right) (https://courses.minia.edu.eg/Attach/16225BT%20333%20(3)%202017.pdf)

☞ ***Life Cycle of Chytridiomycota***

Chytridiomycota have both sexual and asexual reproductive phases.

- ***Asexual reproduction***

Asexual reproduction occurs through the formation of uniflagellate posterior zoospores, which develop into globular, cylindrical, flask-shaped, or irregularly lobed sporangia. The single flagellum is of the whiplash type. Upon finding a suitable substrate, the zoospore retracts its flagellum and encysts before germinating. Germination usually occurs through the formation of a germ tube, but some species may exhibit other germination patterns.

- ***Sexual reproduction***

In primitive chytrids, sexual reproduction occurs through **isogamy**, where gametes are of the same size and shape. These **isogametes resemble zoospores** in morphology. The resulting **zygote typically develops into a thick-walled resting spore (often called a zygospore or resting sporangium), which serves as a survival mechanism under unfavorable conditions.**

Sexual reproduction is well-documented among the **Monoblepharidomycetes**, where a form of **oogamy** is observed—the earliest occurrence of oogamy in the fungal kingdom. In this group:

- The **male gamete (sperm) is motile**, while the **female gamete (egg) is stationary**.
- The **oogonium** produces eggs, while the **antheridium** produces male gametes.
- After fertilization, the **zygote develops into a thick-walled oospore**, which later germinates to produce a new chytrid thallus.

While oogamy is characteristic of Monoblepharidomycetes, **other chytrid groups may exhibit different forms of sexual reproduction.**

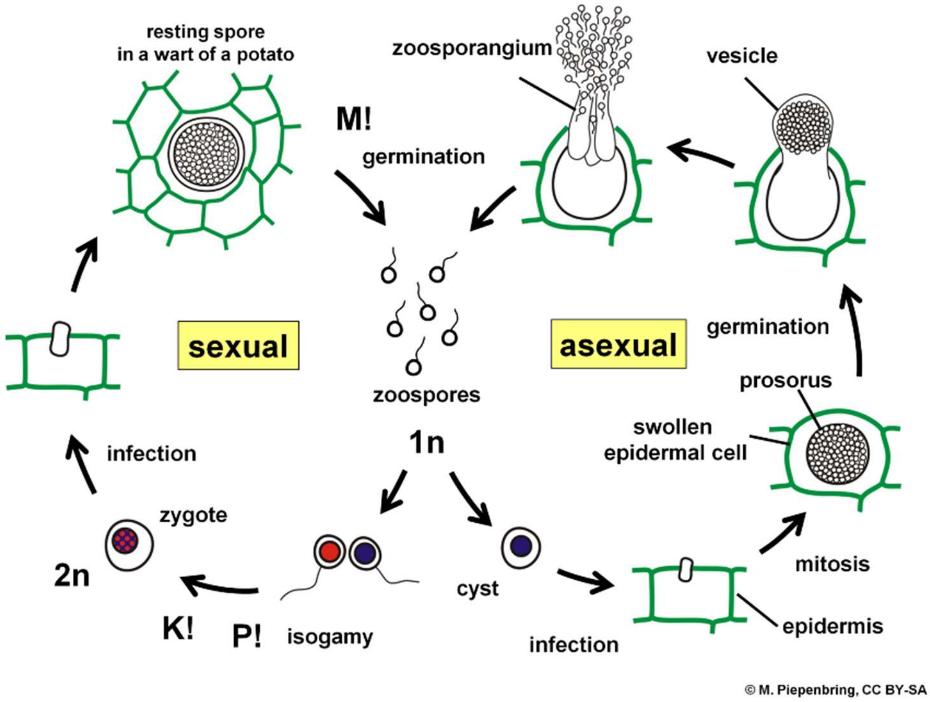



Figure 3.23: Life cycle of Synchytrium endobioticum in potato (Prof. M. Piepenbring)