Introduction to Botany: BIOL 154
Study guide for Exam 2

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Lectures 10–19

Contents

Outline

1 Questions and answers

1.1 Quiz

Final question (2 points)

...

- ...

2 Photosynthesis

2.1 Special case of photosynthesis: C_4 pathway

Photorespiration

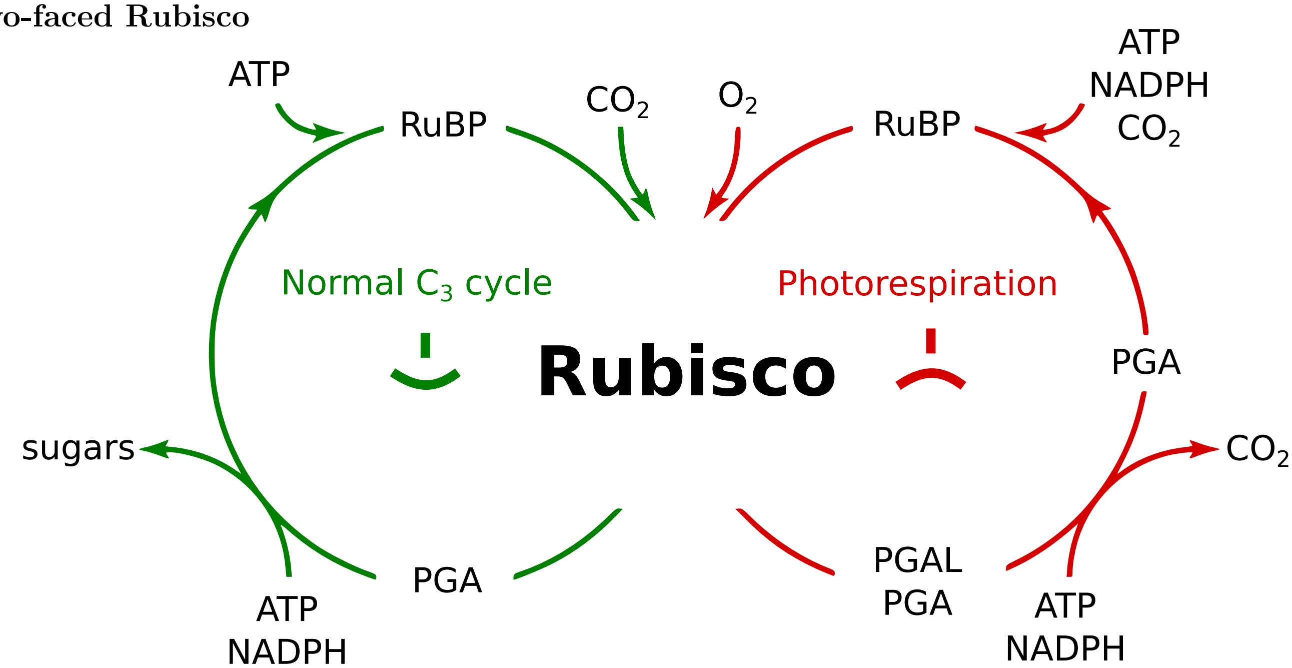
Rubisco is two-faced enzyme, it catalyzes **photorespiration** if the concentration of O_2 and/or temperature is high:

$$O_2 + C_5 \text{ (ribulose biphosphate)} \xrightarrow{Rubisco} \text{3-phosphoglycerate (PGA)} + \text{phosphoglycolate (PGAL)} \longrightarrow \text{glycolate}$$

- To return glycolate into the Calvin cycle, cell must use peroxisomes, mitochondria and spend ATP
- Photorespiration wastes C_5 and ATP

- Photorespiration is said to be an evolutionary relic from times when atmosphere contained little oxygen

Two-faced Rubisco



Minimization of photorespiration

To minimize photorespiration, plants need to increase concentration of CO_2. This is how they do it:

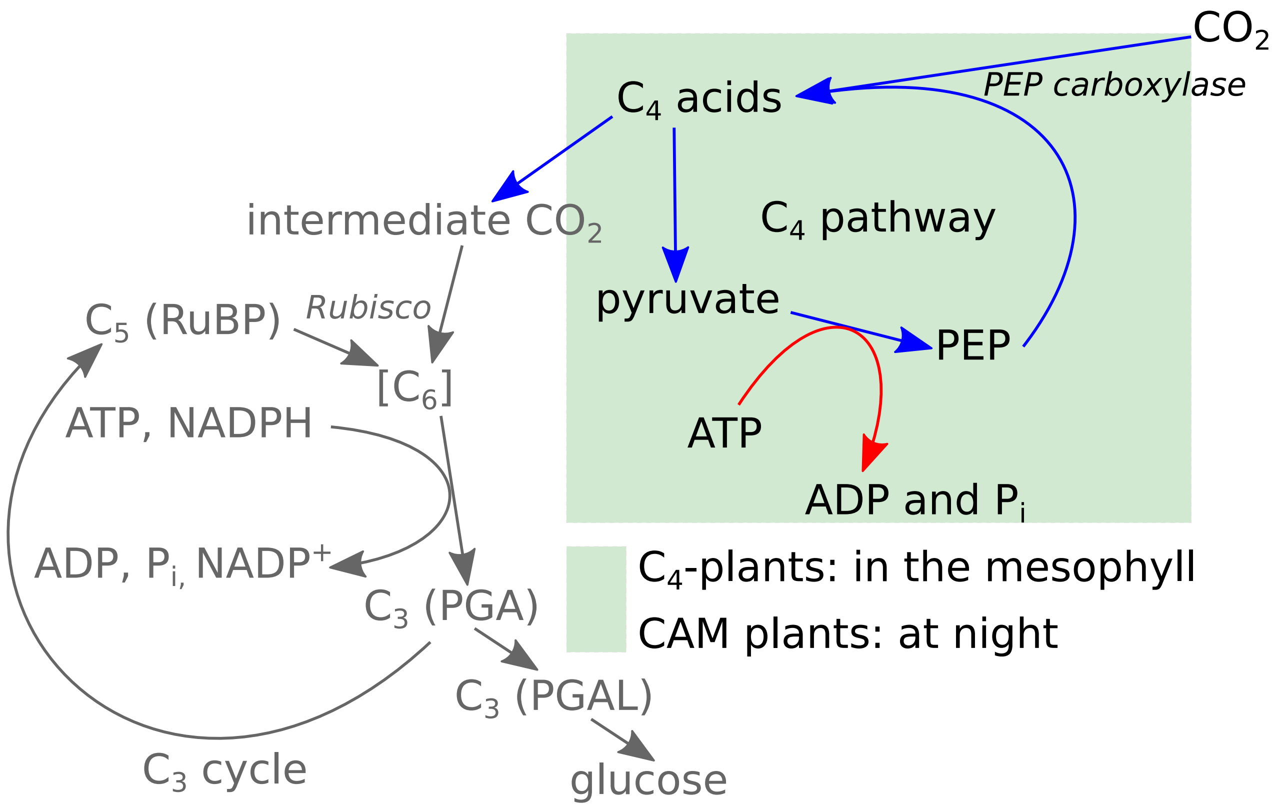
A. $CO_2 + C_5$ (PEP, phosphoenolpyruvate) $\xrightarrow{\text{PEP carboxylase}}$ C_4 (different organic acids): this is the temporarily accumulation of carbon dioxide

B. $C_4 \longrightarrow$ pyruvate + CO_2: release of carbon dioxide will increase its concentration

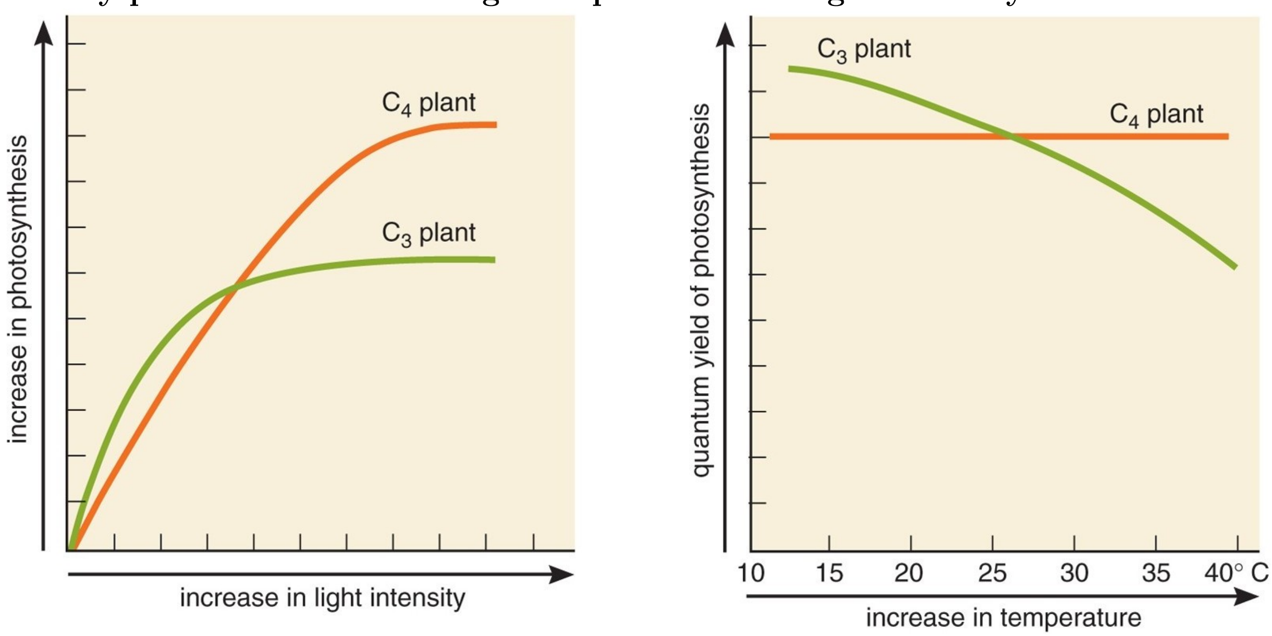
C. Pyruvate + ATP $\longrightarrow$ PEP + ADP + P_i: PEP recovery costs ATP! (but **less** then photorespiration)

Processes above called C_4 pathway, it is an addition to Calvin (C_3) cycle in order to increase concentration of CO_2

C_4 pathway at-a-glance



C_4-pathway plants feel better at high temperature and light intensity



C_4-pathway plants waste ATP to recover PEP but outperform strict C_3 plants when concentration of oxygen is high

2.2 C_4 and CAM plants

C_4 and CAM plants both use C_4 pathway

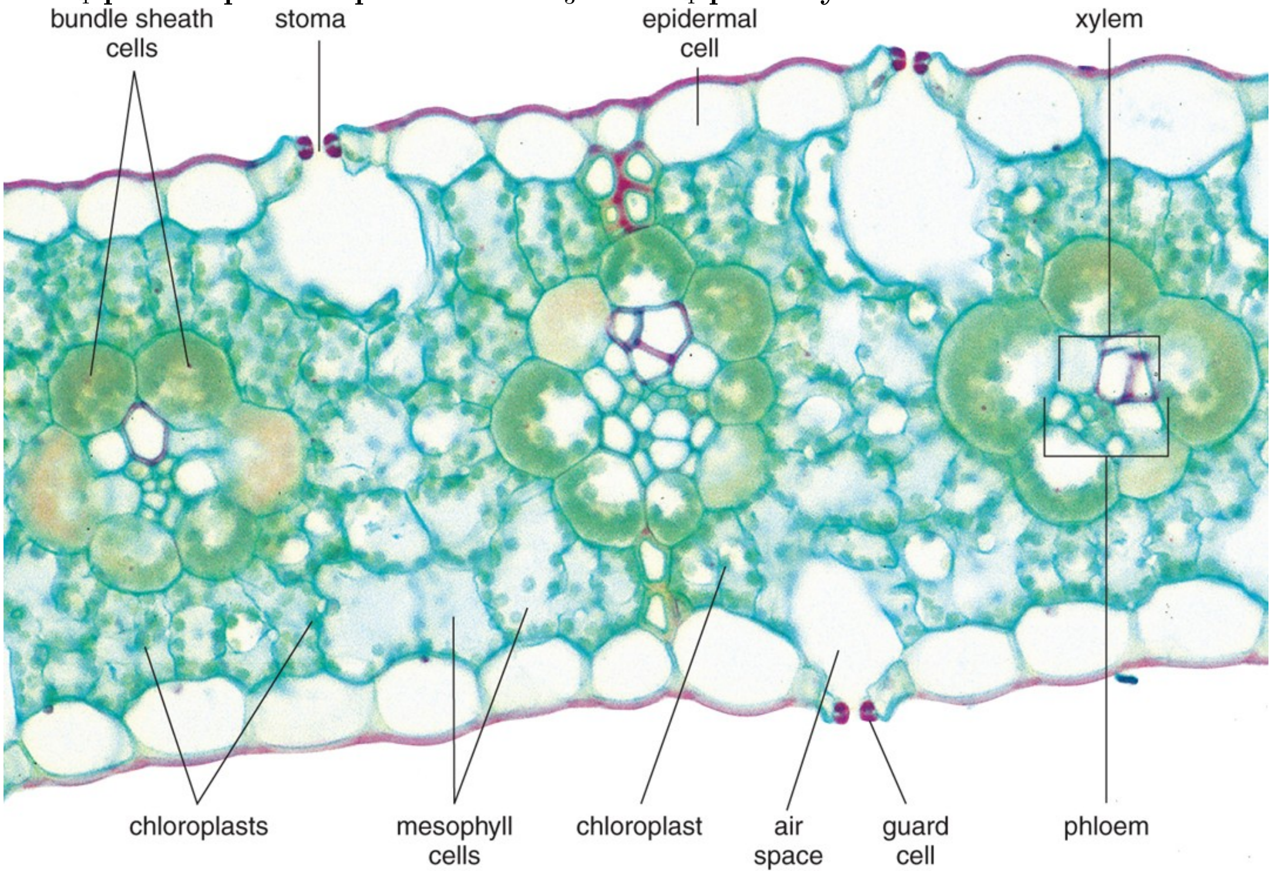
- **CAM-plants** which drive C_4 cycle at nights:
  - This is a **temporal** separation between accumulation of CO_2 and photosynthesis)

- CAM-plants (17,000 species, 7% of plant biodiversity) are mostly succulents from different orders and families (e.g., cacti—Cactaceae from Caryophyllales), other examples are bromeliads like pineapple.

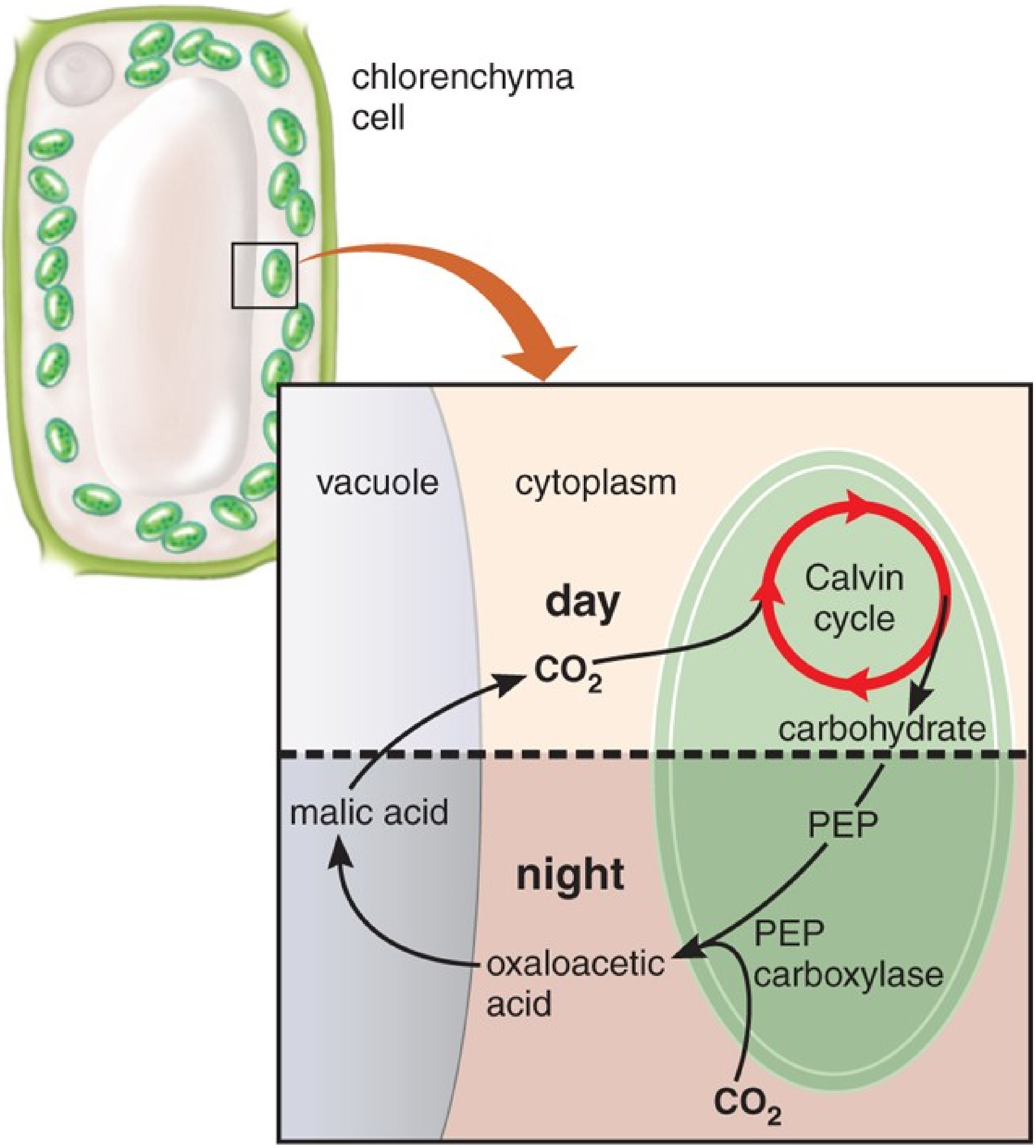
- **C_4-plants** which drive C_4 in mesophyll cells and C_3 in bundle sheath cells:
  - This is a **spatial** separation between accumulation of CO_2 and photosynthesis: C_4 pathway is located in "normal" mesophyll cells whereas the Calvin cycle is separated to **bundle sheath cells**.
  - C_4-plants (7,300 species, 3%) are especially common among Poales (grasses order, e.g., corn, millet, sorghum) and Caryophyllales (pink order)

There are plants which combine C_4 and CAM (*Portulacaria*) and even C_3 and CAM (*Clusia*).

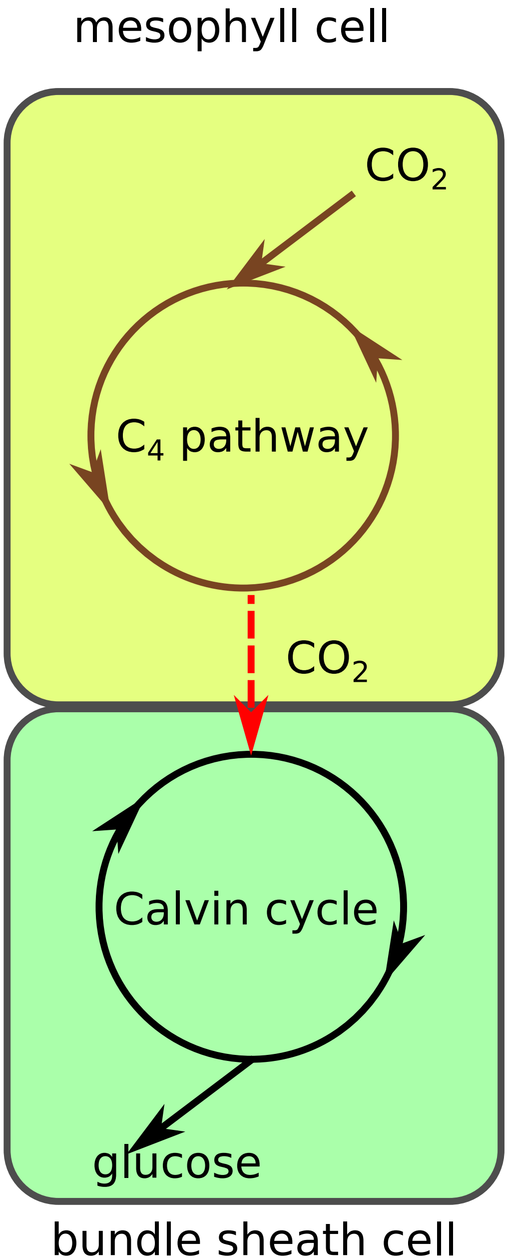
Leaf of C_4 plant: spatial separation of C_3 and C_4 pathways

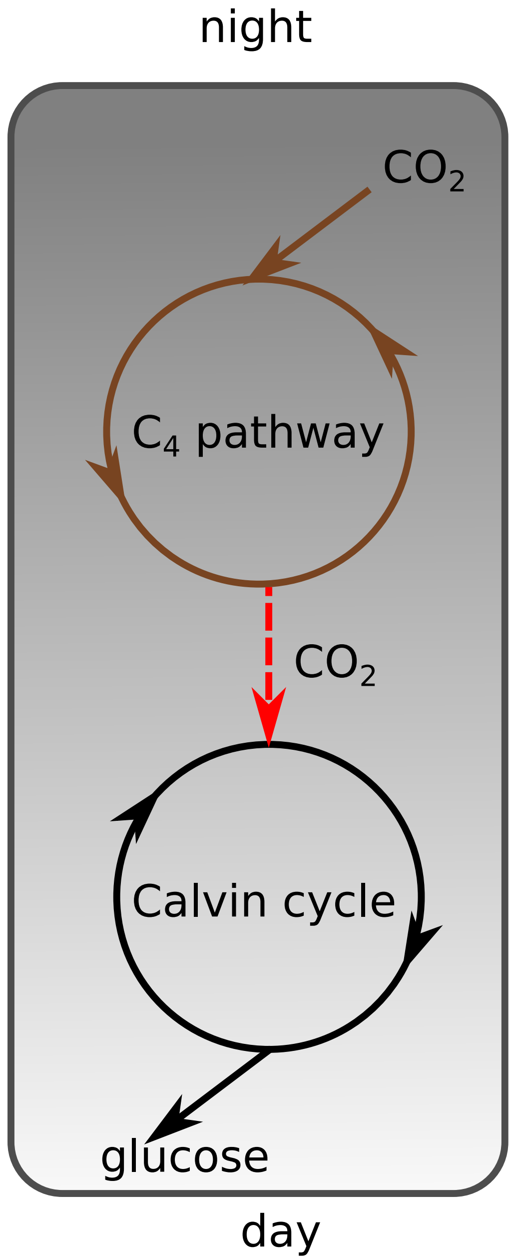


CAM plants separate C_3 and C_4 pathways in time



CAM plants and C_4 plants


mesophyll cell
CO_2
C_4 pathway
CO_2
Calvin cycle
glucose
bundle sheath cell


night
CO_2
C_4 pathway
CO_2
Calvin cycle
glucose
day

Jade plant


CAM is named after the family Crassulaceae, Jade plant (*Crassula ovata*) family

Corn

Corn (*Zea mays*) is the C_4 plant which minimizes photorespiration at higher temperatures

True respiration

- The common misconception about plants is that their only energy-related metabolic process is photosynthesis:

$$CO_2 + H_2O + \text{energy} \longrightarrow \text{carbohydrates} + O_2$$

- However, as most eukaryotes, plants have mitochondria in cells and use *aerobic* (oxygen-related) respiration to obtain energy:

$$\text{carbohydrates} + O_2 \longrightarrow CO_2 + H_2O + \text{energy}$$

- Typically, plants spend much less oxygen in respiration then they make in photosynthesis. However, at nights plants do exactly the same as animals, and make only carbon dioxide!

Final question (2 points)

...

Summary

- **Photosynthesis** is a sum of light-dependent and light-independent reactions
- **Light stage** of photosynthesis results in accumulation of energy and hydrogen, and release of oxygen
- **Enzymatic stage** of photosynthesis results in synthesis of organic molecules
- C_4 and CAM plants accumulate and then release carbon dioxide and therefore increase its concentration

For Further Reading

References

[1] A. Shipunov. *Introduction to Botany* [Electronic resource]. Mode of access: `http://ashipunov.info/shipunov/school/biol_154`

Outline

3 Questions and answers

3.1 Quiz

Results of the first exam

Results of the first exam

Lab attendance

Lab attendance

Final question (2 points)

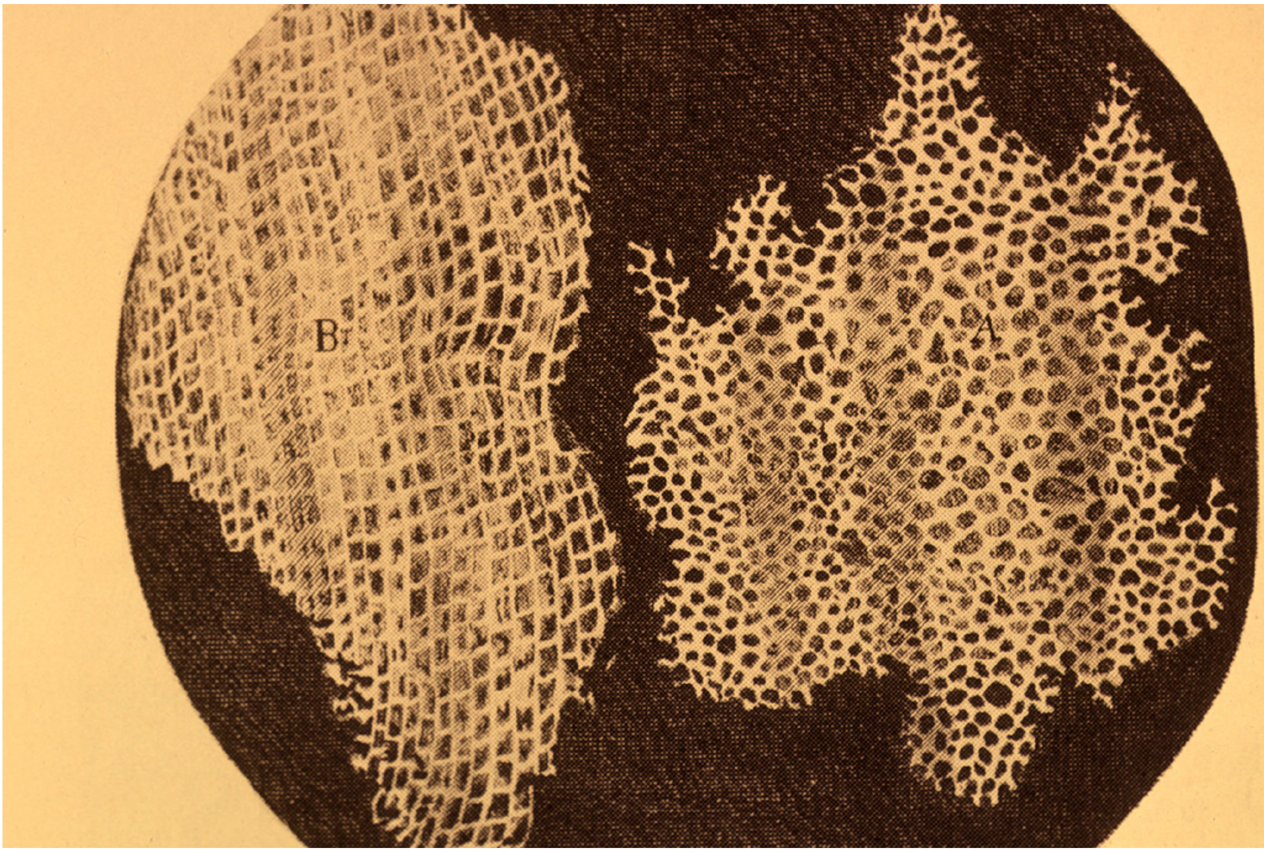
Why do plants need a C_4 pathway?

- They need it to suppress photorespiration

4 Plant cell

4.1 Discovery of cell

Discovery of cells



In 1665, Robert Hooke looked at cork tissue under microscope and found “little boxes or cells distinct from one another ... that perfectly enclosed air”

Hooke’s microscope

National Library of Medicine

Cell theory

A. All plants and animals are composed of cells (1839, Matthias Schleiden and Theodor Schwann)

B. Cell is most basic unit (atom) of life (1839, Matthias Schleiden and Theodor Schwann)

C. All cells arise by reproduction from previous cells (1858, Rudolf Virchow)

Miscroscopes

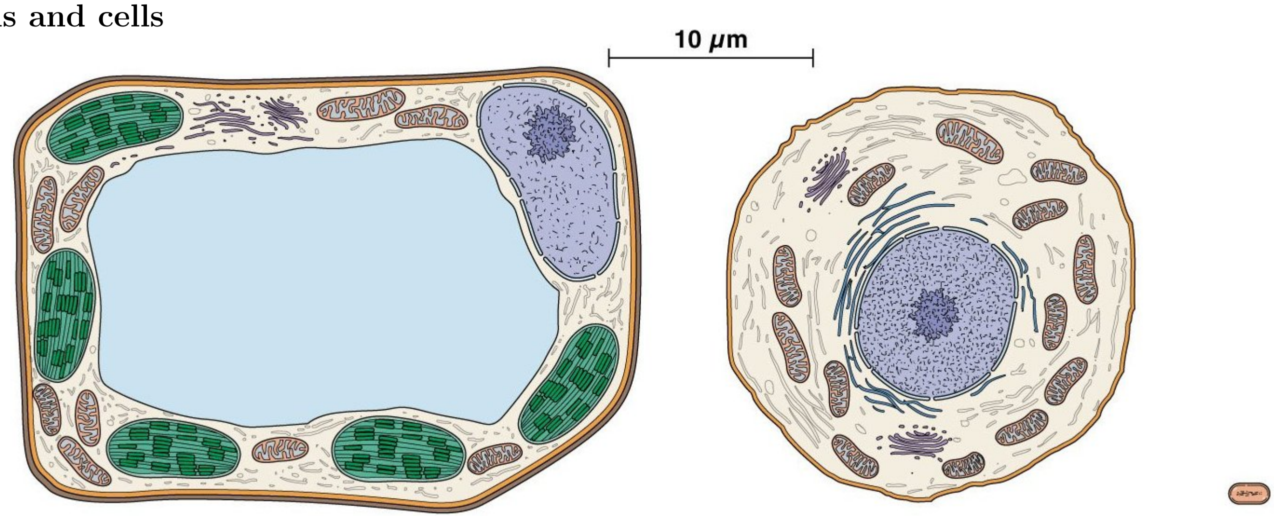
Light microscopy was an early technological breakthrough that contributed to our understanding of cell structure. Dissectiscopes use reflected light, microscopes use translucent light. Magnification is of 10^3 order.

Transmission electron microscopy (TEM) allows us to see the internal organization of cells and organelles. Use translucent electronic "light" (electronic beam) which kills objects. Objects are often stained with osmium (Os). Magnification if of 10^7 order.

Scanning electron microscopy (SEM) provides an image of the surface of cells and organisms. Use reflected electronic "light" (electronic beam). Objects are covered with thin layer of gold (Au). Magnification if of 10^6 order.

4.2 Structure of cell

Cells and cells



Eukaryotic and prokaryotic cells are fundamentally different

Plant cell

List of cell structures

- Cell membrane
- Cytoplasm
- Nucleus, nuclear pore, nucleolus, chromatine
- **Chloroplast, thylakoids**
- Mitochondrion, cristae
- ER (endoplasmatic reticulum/network)
- Goldgi apparatus (AG)
- **Vacuoles**, lysosomes, peroxisomes
- Ribosomes
- **Cell wall**

Chloroplasts and mitochondria are both results of symbiogenesis

Final question (2 points)

...

Summary

- Eukaryotic and prokaryotic cells are cells of different levels of organization
- Eukaryotic cell is a "second-level" cell, cell from cells, ecosystems
- Chloroplasts and mitochondria are both results of symbiogenesis

For Further Reading

References

[1] A. Shipunov. *Introduction to Botany* [Electronic resource]. Mode of access: `http://ashipunov.info/shipunov/school/biol_154`

Outline

5 Questions and answers

5.1 Quiz

Quiz question (2 points)

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- ...

6 Plant cell

Plant cell

List of cell structures

- *Cell membrane*
- *Cytoplasm*
- *Nucleus, nuclear pore, chromosomes*
- *Chloroplast, thylakoids*
- *Mitochondrion, cristae*
- ER (endoplasmatic reticulum/network)
- Goldgi apparatus (AG)

- **Vacuoles**, lysosomes, peroxisomes
- Ribosomes
- **Cell wall**

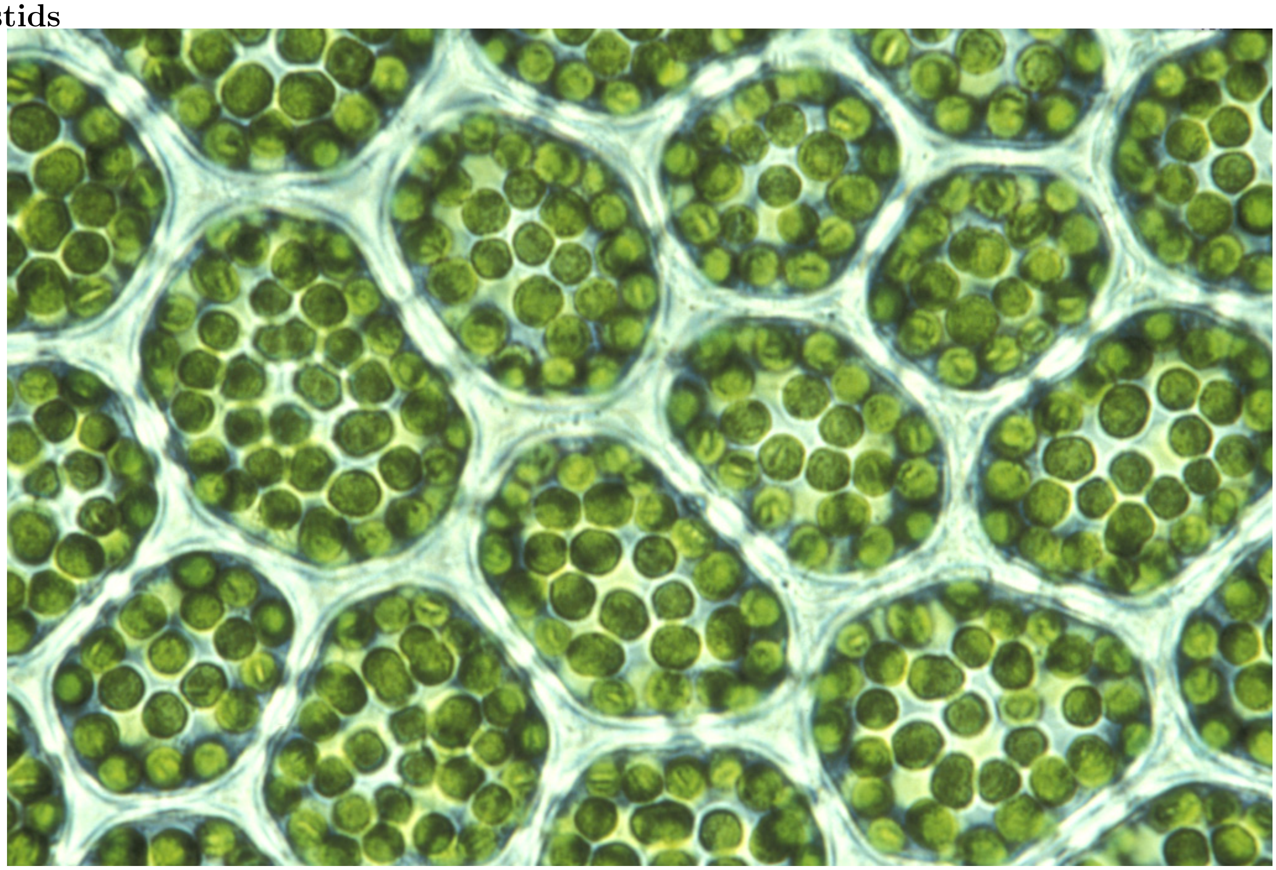
Chloroplasts and mitochondria are both results of symbiogenesis

6.1 Cells in cells: mitochondria and chloroplasts

Symbiogenesis

- Small, rigid procaryotic cells became larger to escape from predators
- To keep all parts of larger cell communicable, they developed cytoplasm motility based on **actin** protein
- Cytoplasm motility allowed for **phagocytosis** so they became predators
- These predator cells captured many bacteria and digested them in lysosomes; they also developed nucleus to (a) guard DNA and (b) prevent the horizontal transfer of genes from alien organisms
- Some of prey were not digested (probably, by mistake) but were still useful because they provide ATP
- This condition were naturally selected, and these prey became mitochondria; mitochondria originated from purple bacteria
- Some mitochondial eukaryotes also captured cyanobacteria (plants$_1$) and became **algae** with chloroplasts

Plastids

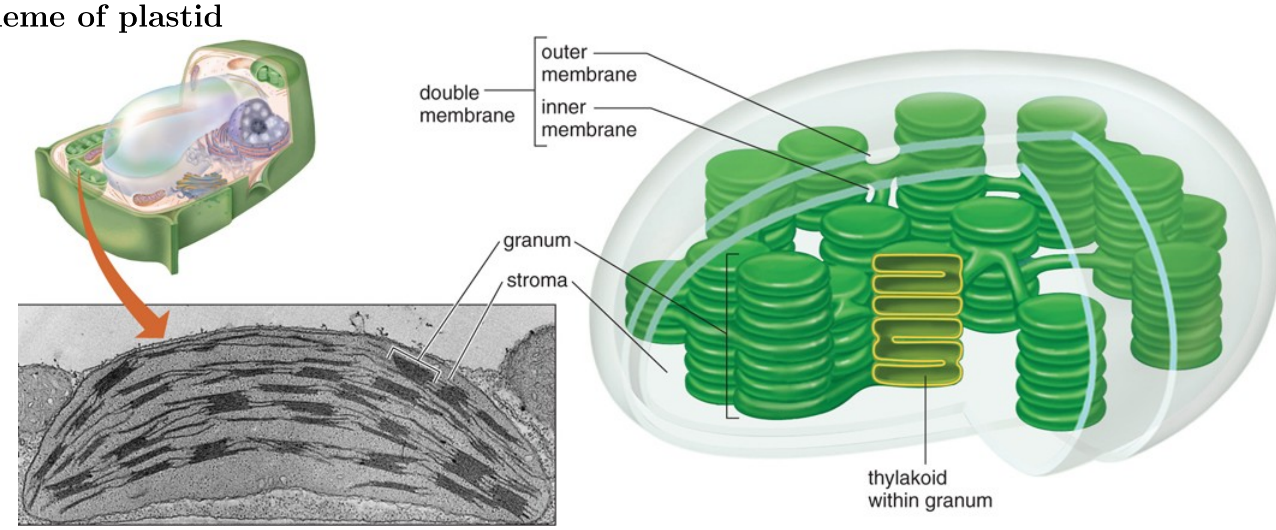


Green plastids (chloroplasts) in leaf cells of *Rhizomnium pseudopunctatum* (LM ×500)

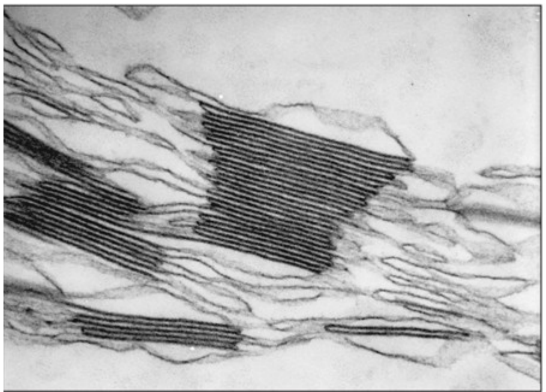
Plastid structure

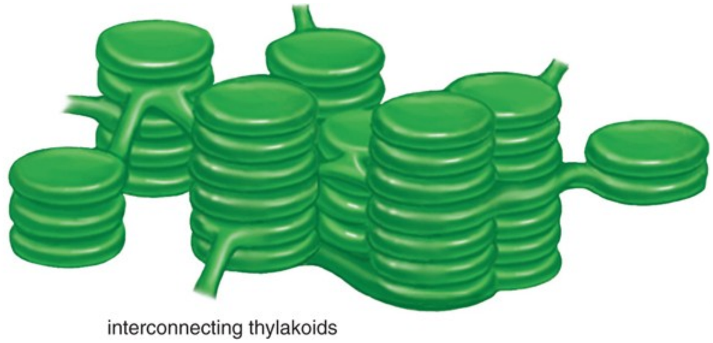
Thylakoids, stroma and starch granules (TEM $\times 37,500$)

Scheme of plastid



Grana



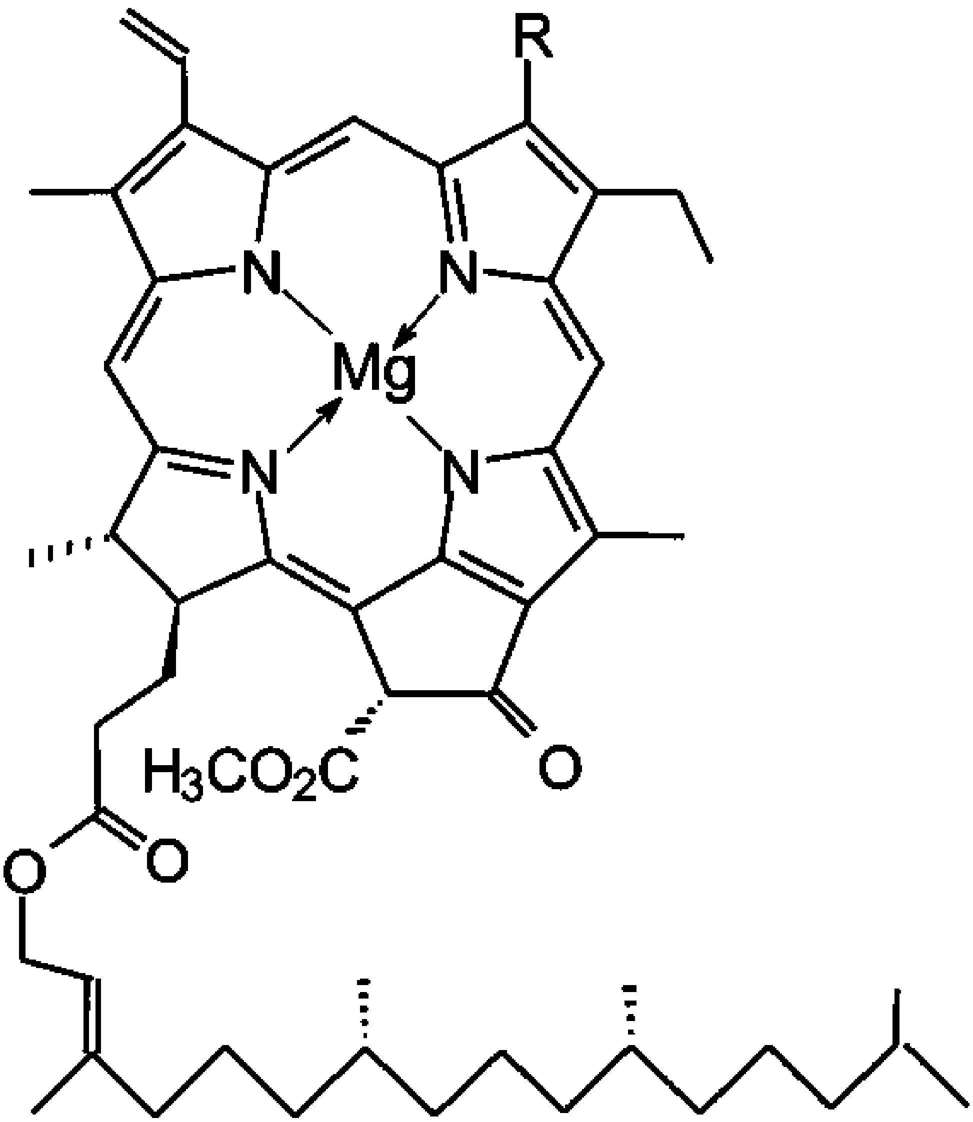


Grana is plural, **granum** singular.

Pigments

- Chlorophylls (a and b) are photosynthetic lipids, including magnesium (Mg)
- Carotenoids facilitate photosynthesis, responsible for autumn colors

Chlorophylls *a* and *b*



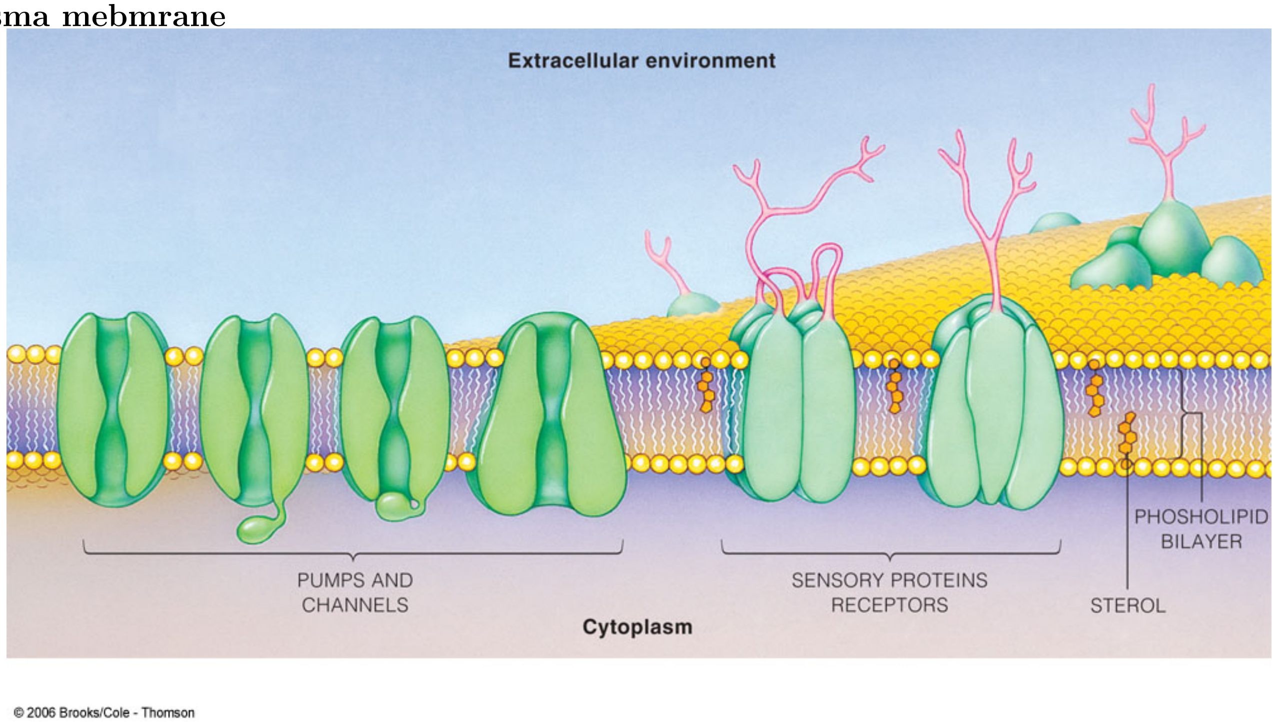
chlorophyll *a* (R = CH_3)
chlorophyll *b* (R = CH=O)

Mitochondria

Mitochondrion showing foliate *cristae* and matrix granules. Mitochondria are the main energy source (in form of ATP) of the cell (TEM)

6.2 Cell boundaries

Plasma mebmrane

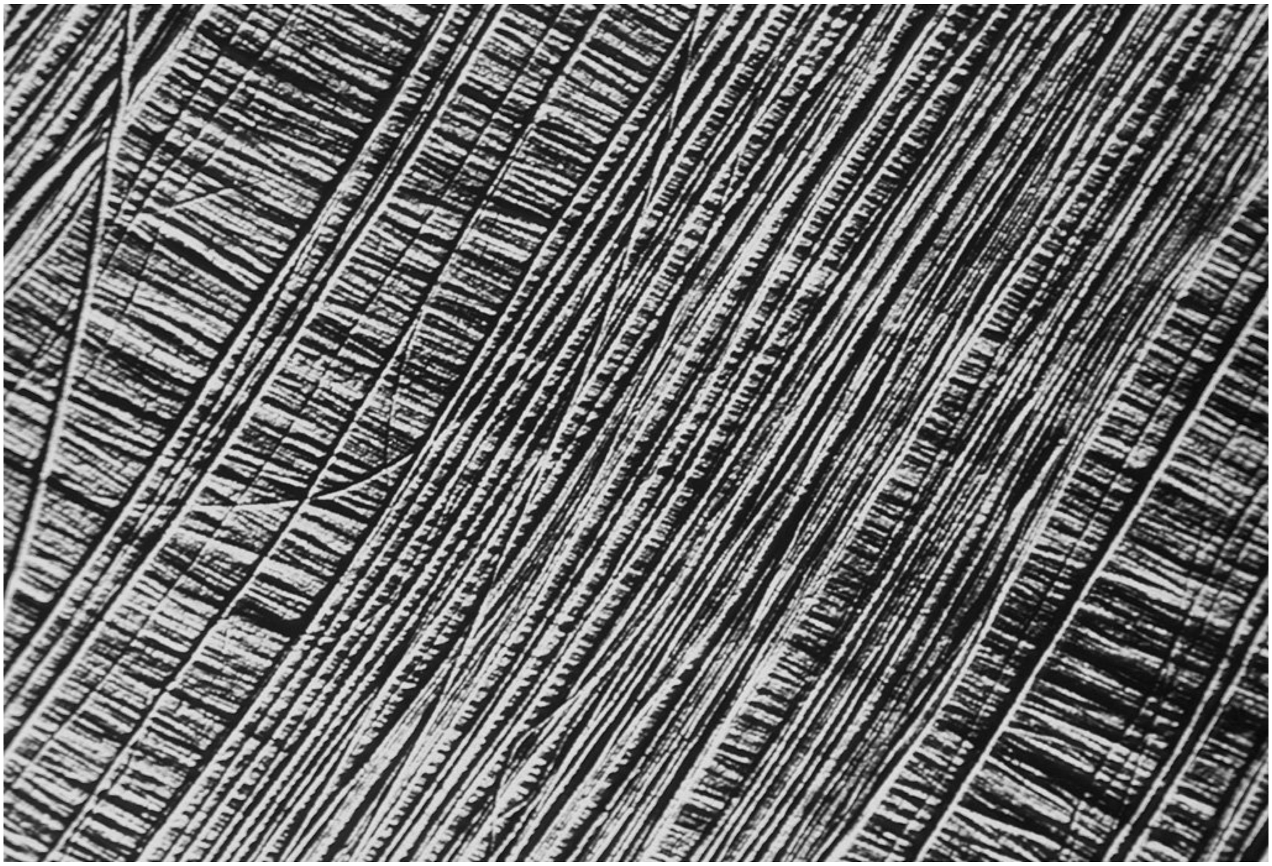


Phospholipids, sterols, proteins: pumps, receptors, channels

Cell wall

Root cells of an onion showing the cell wall (TEM $\times 47,000$)

Fibers

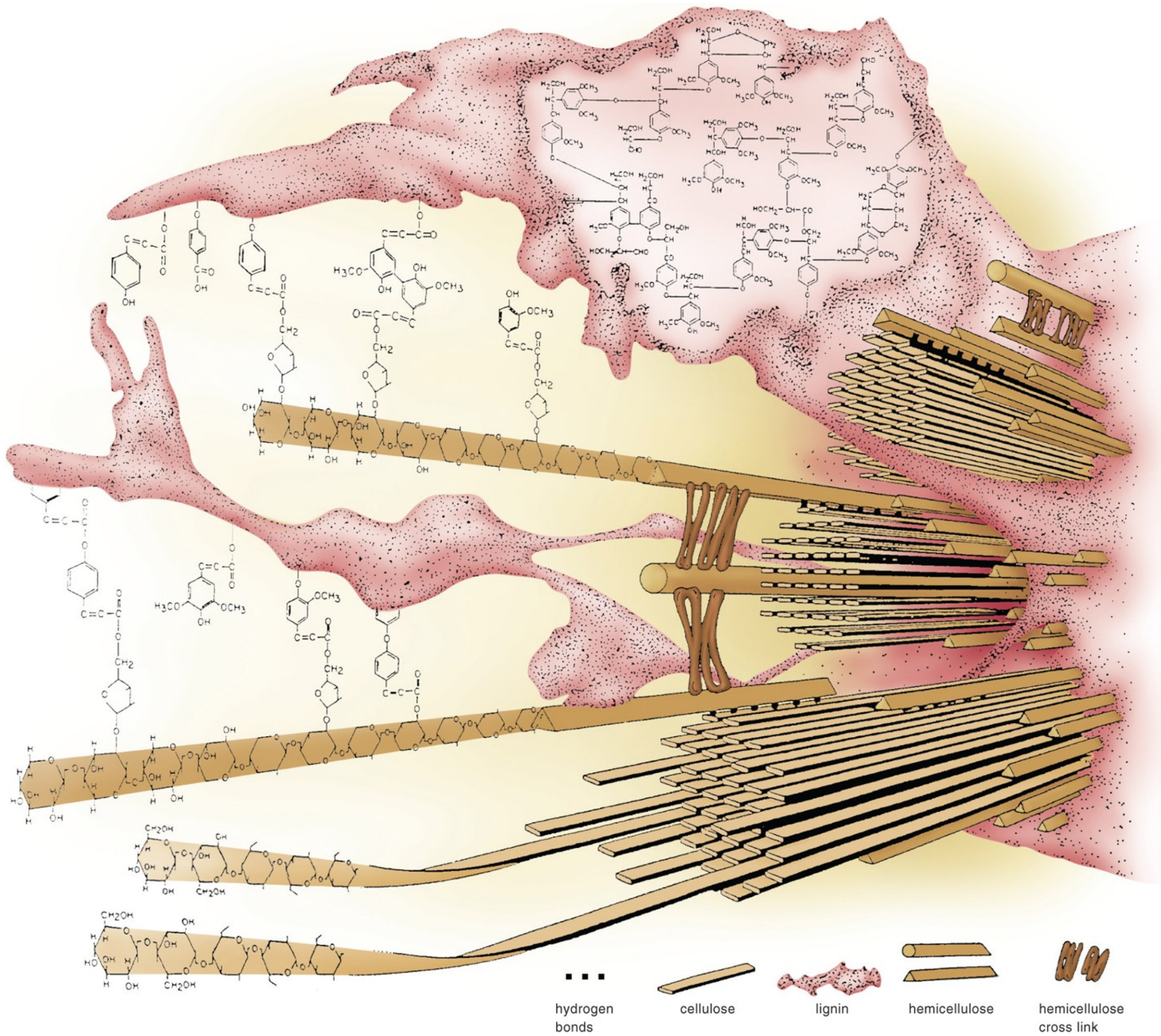


Cellulose fibers in the plant cell wall (SEM)

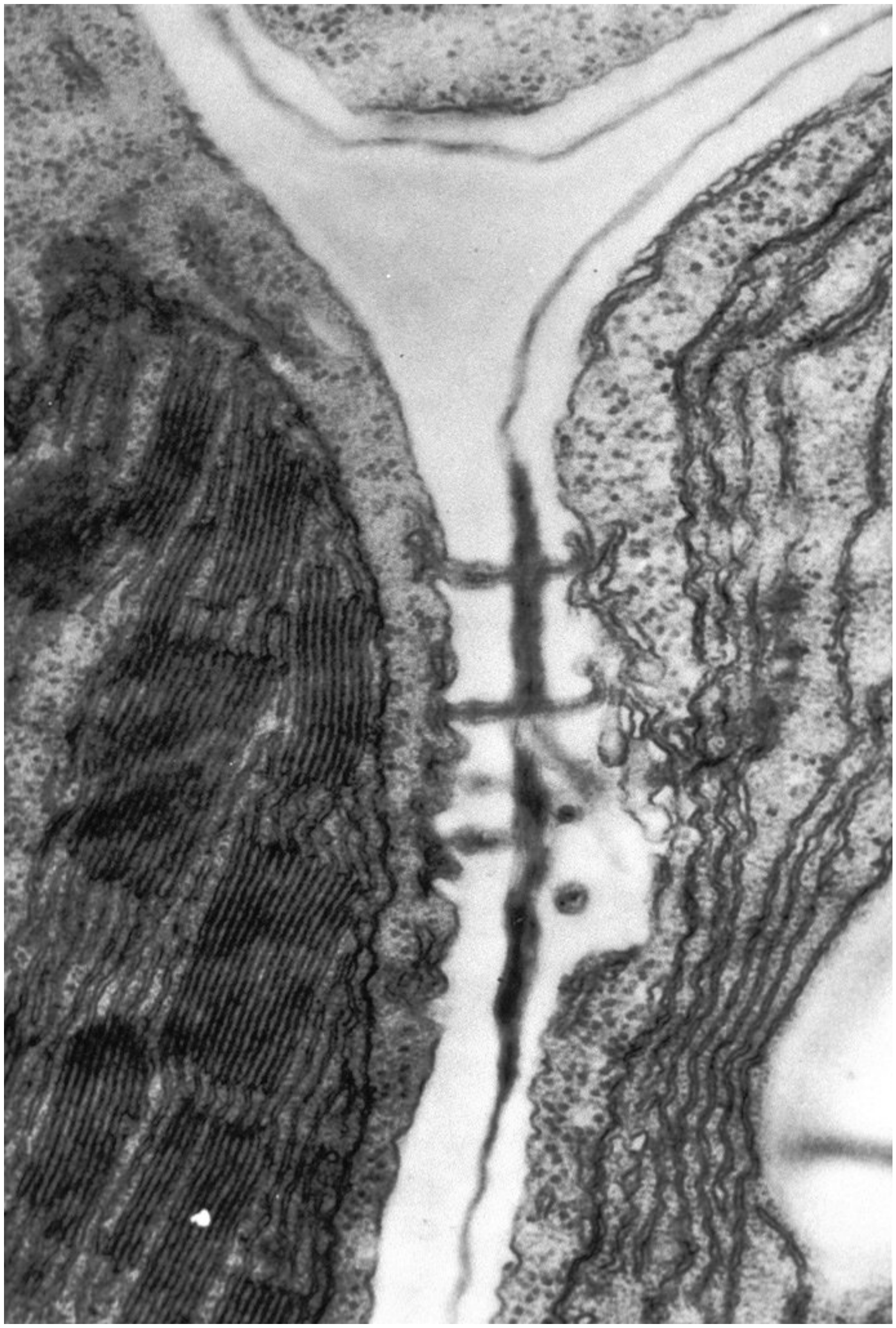
Primary and secondary cell walls

- **Primary cell wall** consists mostly of cellulose and proteins, they are thin and flexible
- **Secondary cell wall** includes hydrophobic lignine and suberine; this inclusion leads to the death of cell. However, dead cells are very useful for plants

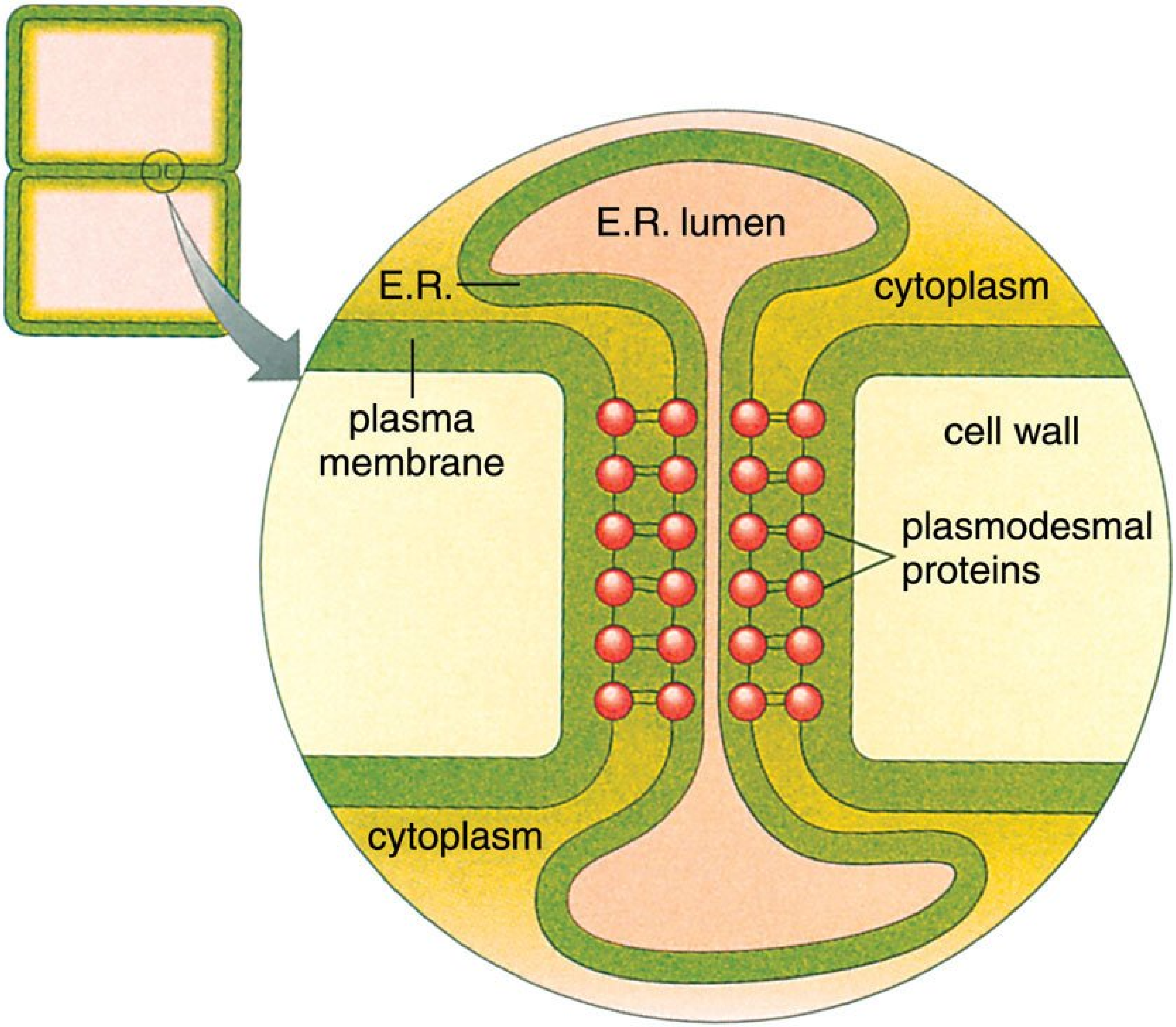
Secondary cell wall: molecules



Plasmodesmata


Plasmodesmata in a corn leaf between a mesophyll cell and a bundle sheath cell (TEM)

Plasmodesmata: shematic view



E.R. = endoplasmic reticulum (endoplasmic network)

Quiz question (2 points)

...

Summary

- Eukaryotic and prokaryotic cells are cells of different levels of organization
- Eukaryotic cell is a "second-level" cell, cell from cells, ecosystems
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- Secondary cell walls cover dead cells

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Outline

7 Questions and answers

7.1 Quiz

Quiz question (... points)

...

- ...

8 Plant cell

8.1 Cell boundaries

Vacuoles, osmosis and turgor pressure

- If cell vacuoles contain more concentrated solution of salts then water surrounding cell (i.e., water outside is *hypotonic*), water will flow inside a cell. It is called **osmosis**
- Cell wall prevents cell from explosion due to high **turgor pressure**
- When water flows outside a cell, cell content will shrink: this is **plasmolysis**

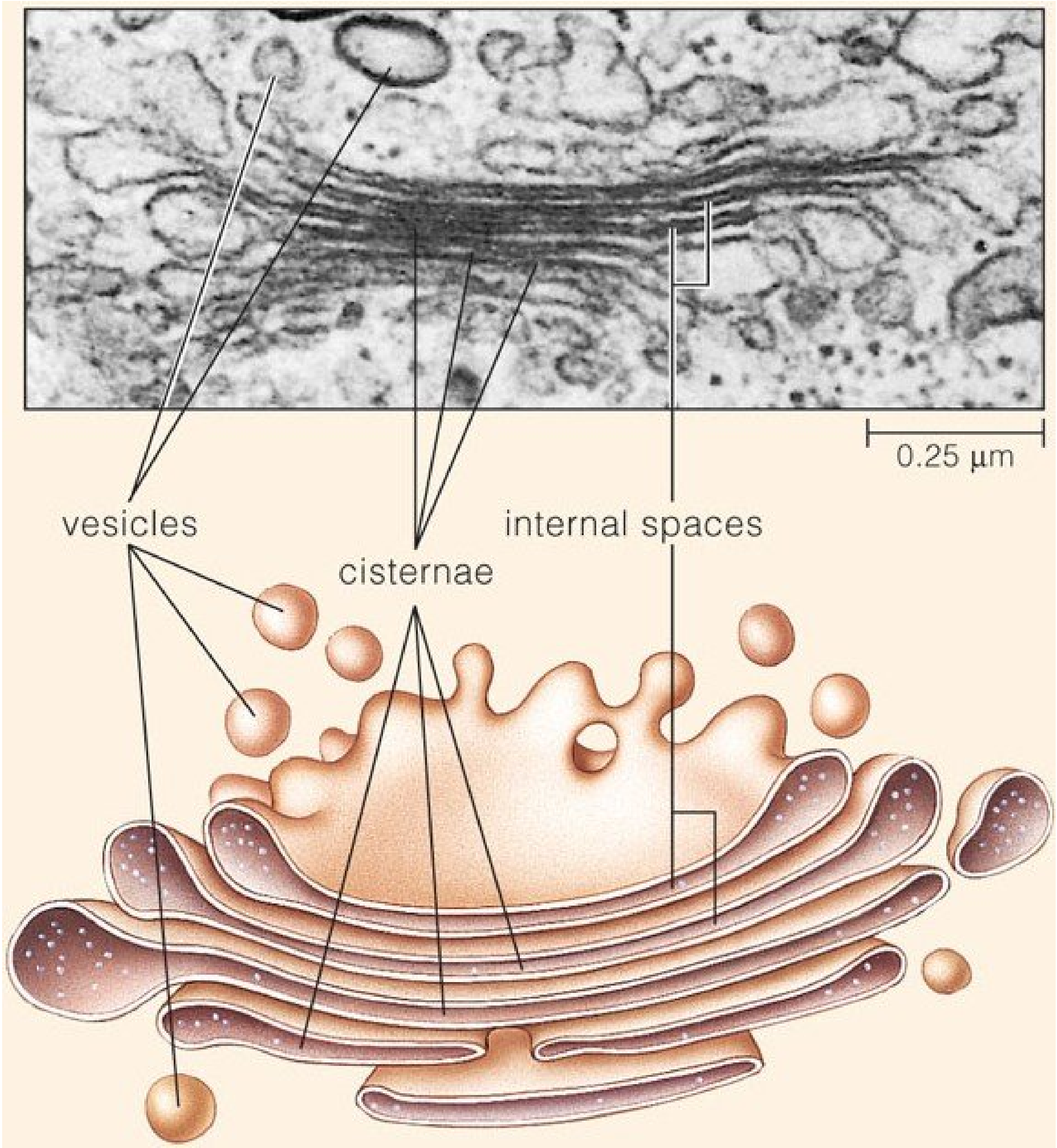
Symplast and apoplast

- **Symplast**—name for continuous cytoplasm in set of cells
- **Apoplast**—space outside cell; area of considerable metabolic activity

Endoplasmatic reticulum (network), ER

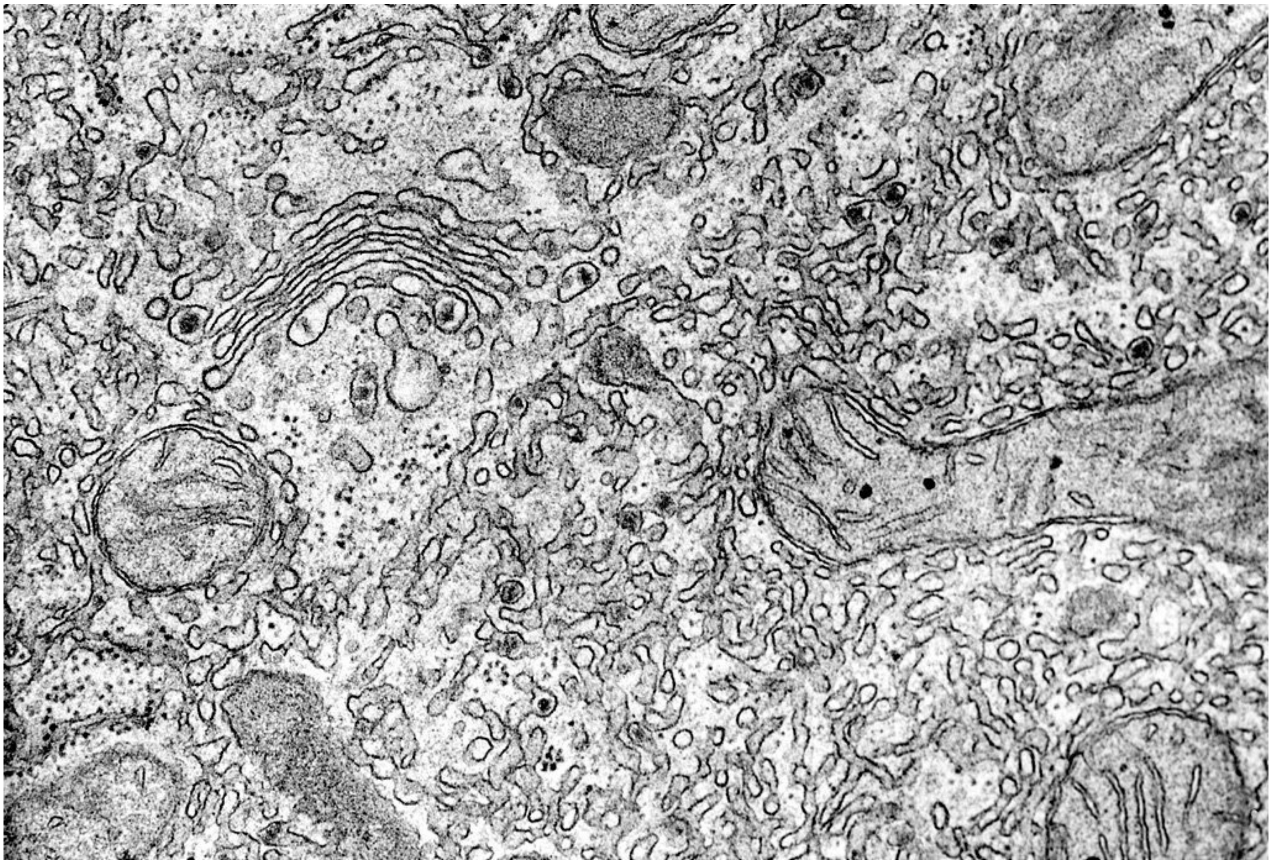
Rough endoplasmic reticulum with ribosomes along outer surface. Manufactures many proteins destined for secretion or for incorporation into membranes (TEM)

Goldgi apparatus (dictyosomes)



The Golgi is an organelle composed of stacks of flattened, membranous sacs mainly responsible for modifying, packaging, and sorting proteins that will be secreted or targeted to other organelles of the internal membrane system or to the plasma membrane

Goldgi apparatus on TEM



Golgi complex and smooth endoplasmic reticulum in a liver cell (TEM)

8.2 Protein synthesis

Nucleus structure

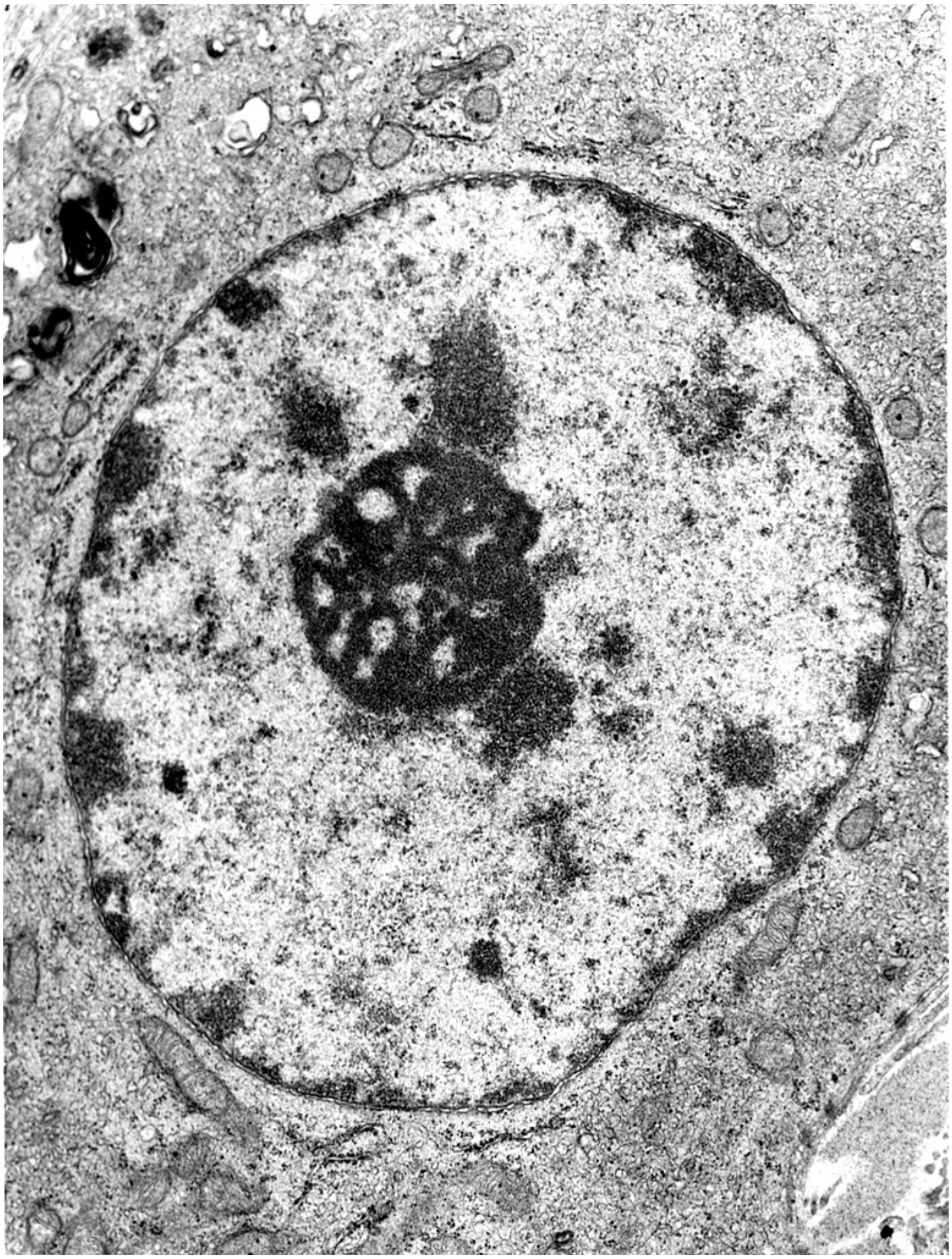
Nuclear envelope Double layered membrane, filaments of protein lamin line inner surface and stabilize structure, inner and outer membranes connect to form pores

Nucleoplasm Portion inside the nuclear envelope

Nucleoli Dark staining bodies within nucleus, site for ribosome synthesis

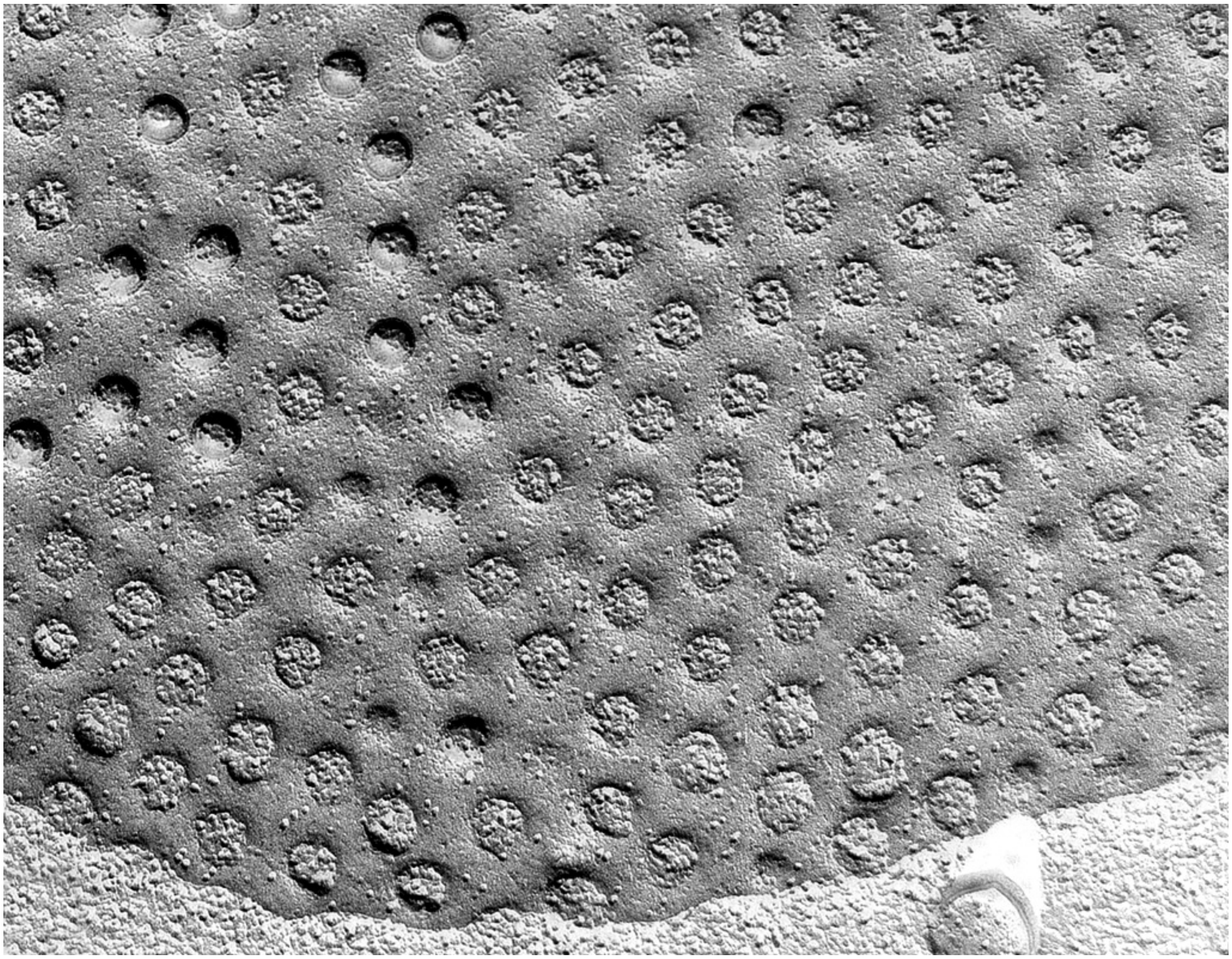
Chromosomes Store genetic information in nucleotide sequences, each chromosome consists of chain of nucleosomes (long DNA molecule and associated histone proteins). When cell is not dividing, chromosomes are frequently seen as **chromatin**.

Nucleus



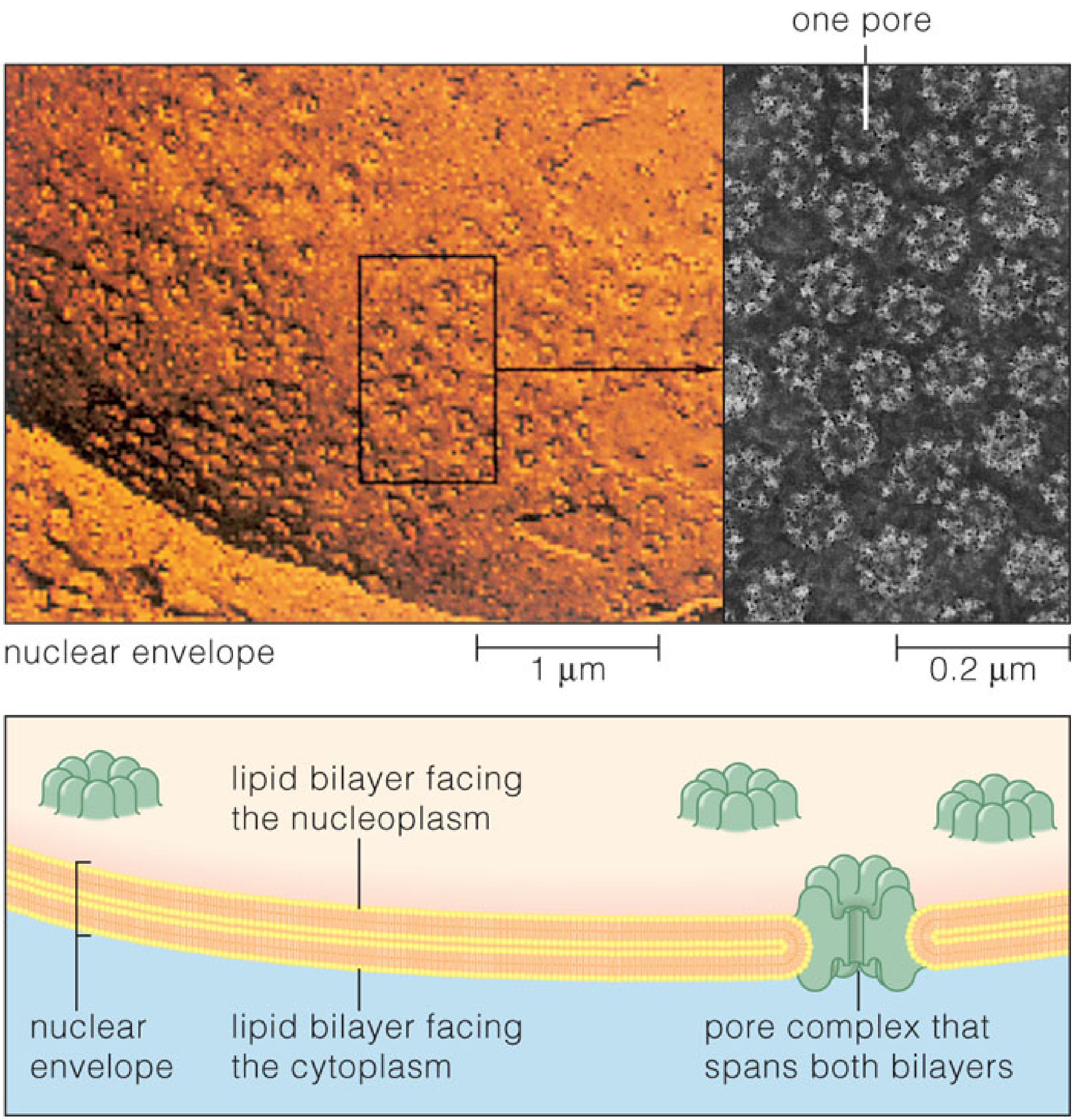
A typical nucleus with a prominent nucleolus (TEM).

Nuclear pores

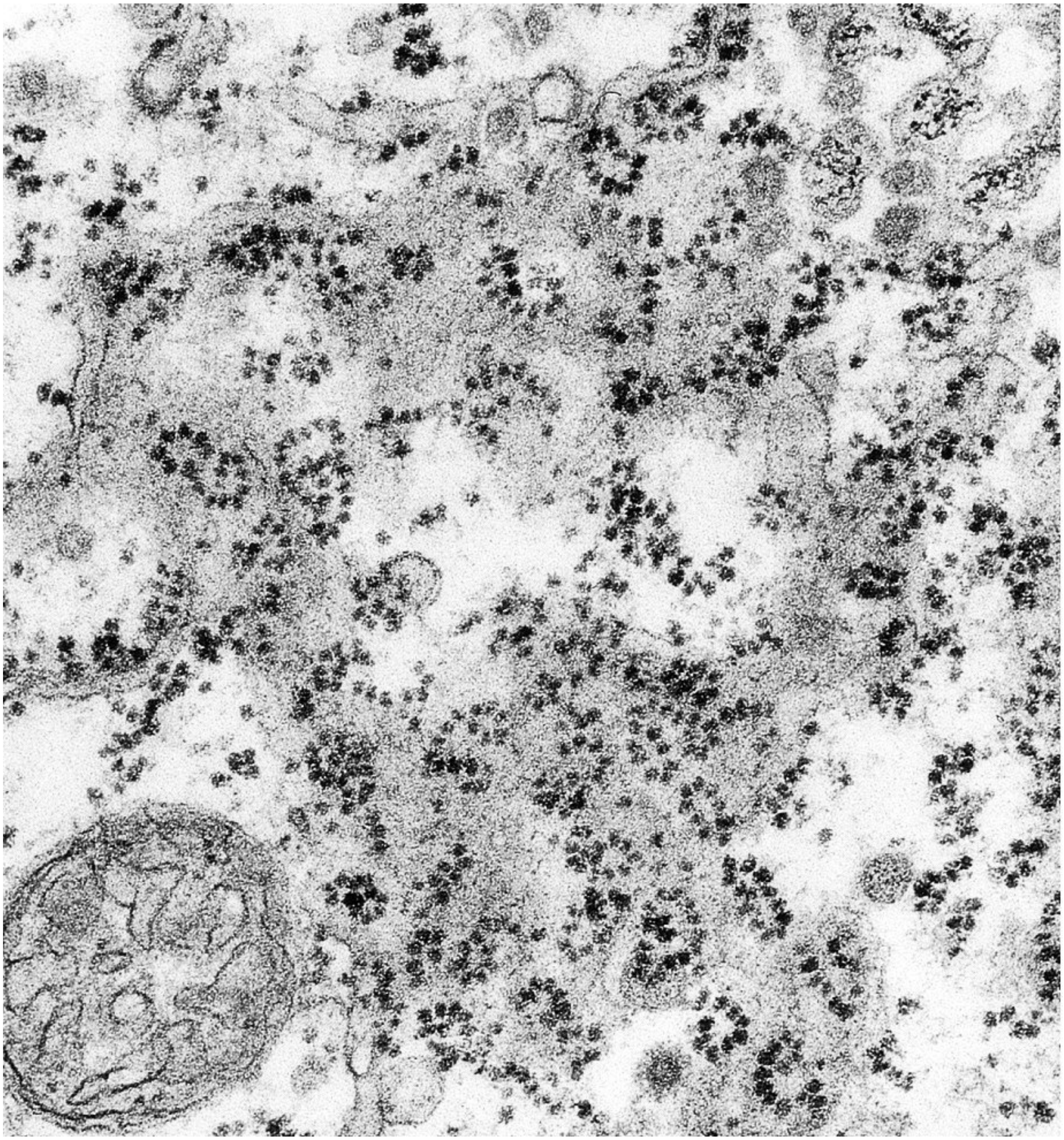


Freeze-fracture technique used to show nuclear pores. Nuclear pores are structures in the nuclear envelope that allow passage of certain materials between the cell nucleus and the cytoplasm (TEM $\times 100,000$)

Nuclear pores and envelope


one pore
nuclear envelope
1 µm
0.2 µm
lipid bilayer facing
the nucleoplasm
nuclear
envelope
lipid bilayer facing
the cytoplasm
pore complex that
spans both bilayers

Ribosomes



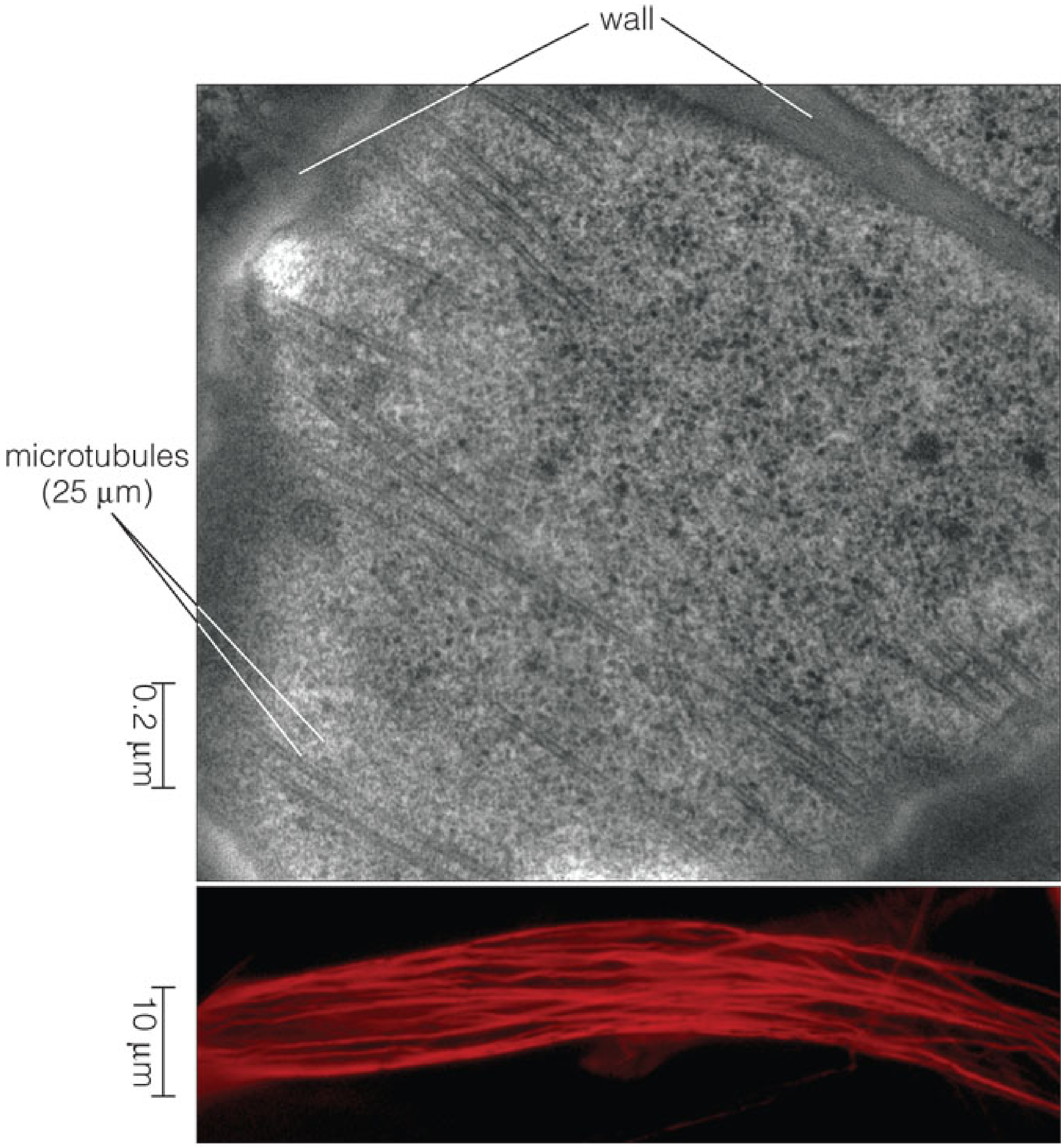
8.3 Other cell structures

Cellular skeleton

Collection of long, filamentous structures within cytoplasm:

- **Microtubules**. Movement based on tubulin-kinesins interactions. They are key organelles in cell division, form basis of cilia and flagella, serve as guides for the construction of cell wall
- **Microfilaments**. Movement based on actin-myosin interactions. Serve as guides for movement of organelles within cell

Cytoskeleton



9 Mitosis and meiosis

9.1 Mitosis

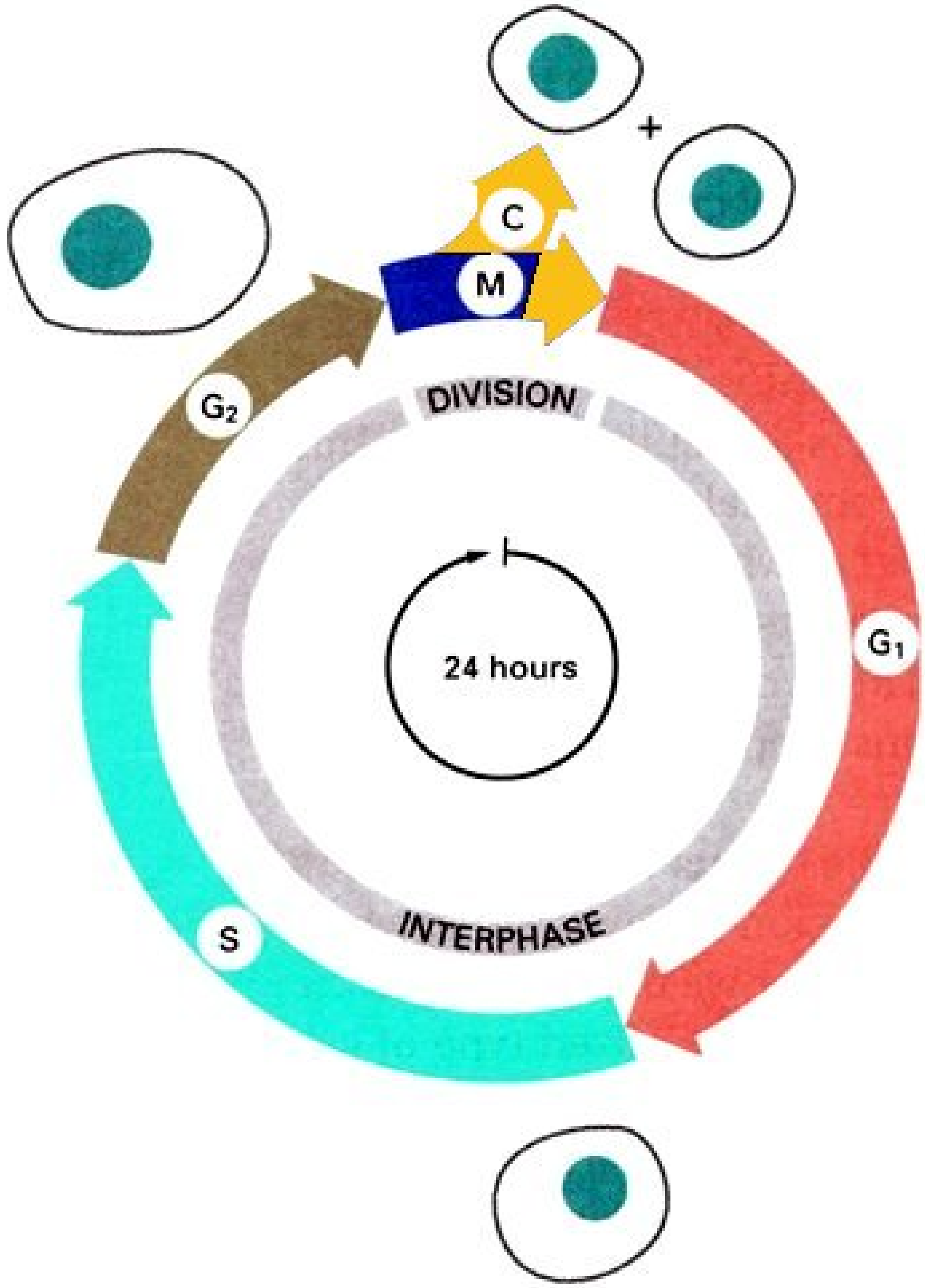
Definition of mitosis

- *Equal cell division, where each of daughter cells receives the same number of chromosomes as a mother cell*
- Chromosome formula: X $\longrightarrow$ I + I
- **The goal of mitosis** is the equal distribution of pre-synthesized DNA
- Mitosis does not change genotype of cells

Mitosis, karyokinesis and cytokinesis

- Mitosis is the kind of nucleus division, **karyokinesis**
- Cytokinesis is a different process, the part of **cell cycle**

Cell cycle



- Interphase
  - Pre-synthetic stage (G_1)
  - Sythetic stage (S): DNA duplicated
  - Post-synthetic stage (G_2)
- Mitosis

  - Prophase
  - Metaphase
  - Anaphase
  - Telophase

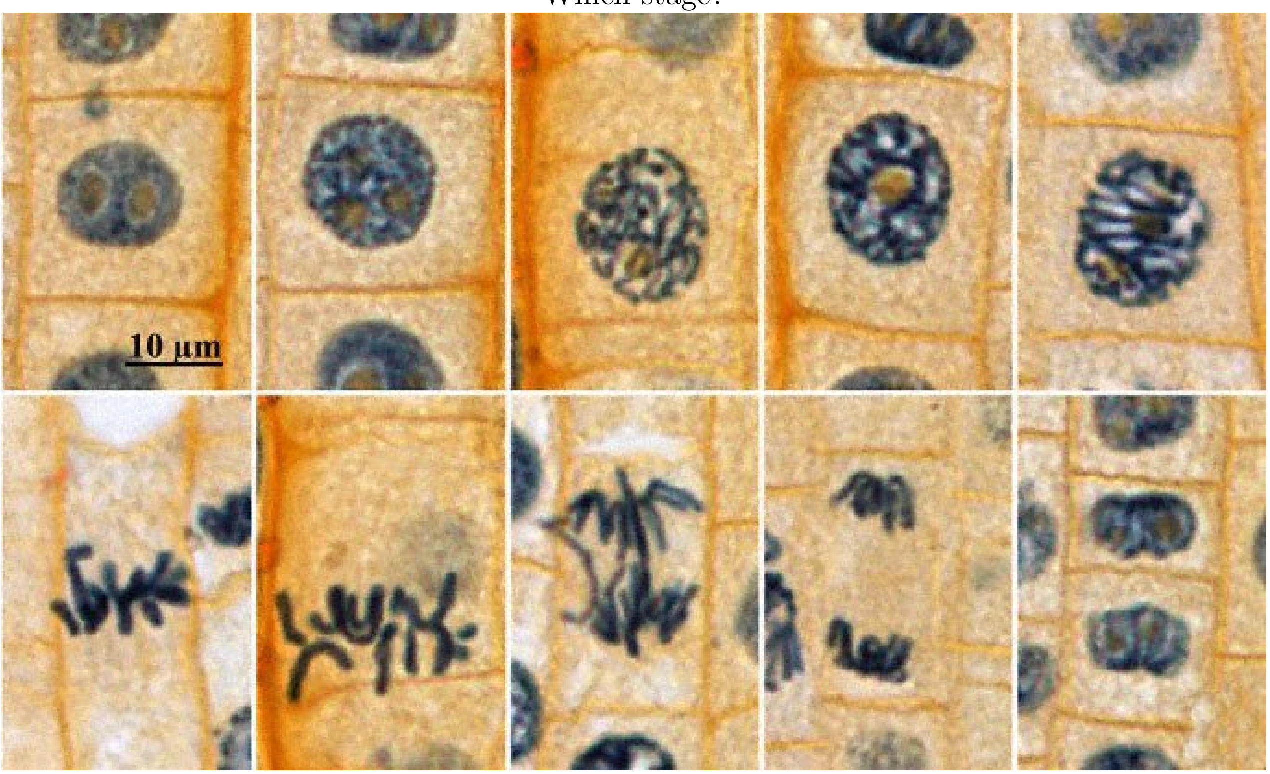
- Cytokinesis

Stages of mitosis

- Prophase
- Metaphase
- Anaphase
- Telophase

Final question (2 points)

Which stage?



Summary

- Eukaryotic and prokaryotic cells are cells of different levels of organization
- Eukaryotic cell is a "second-level" cell, cell from cells, ecosystems
- Chloroplasts and mitochondria are both results of symbiogenesis
- Secondary cell walls cover dead cells

For Further Reading

References

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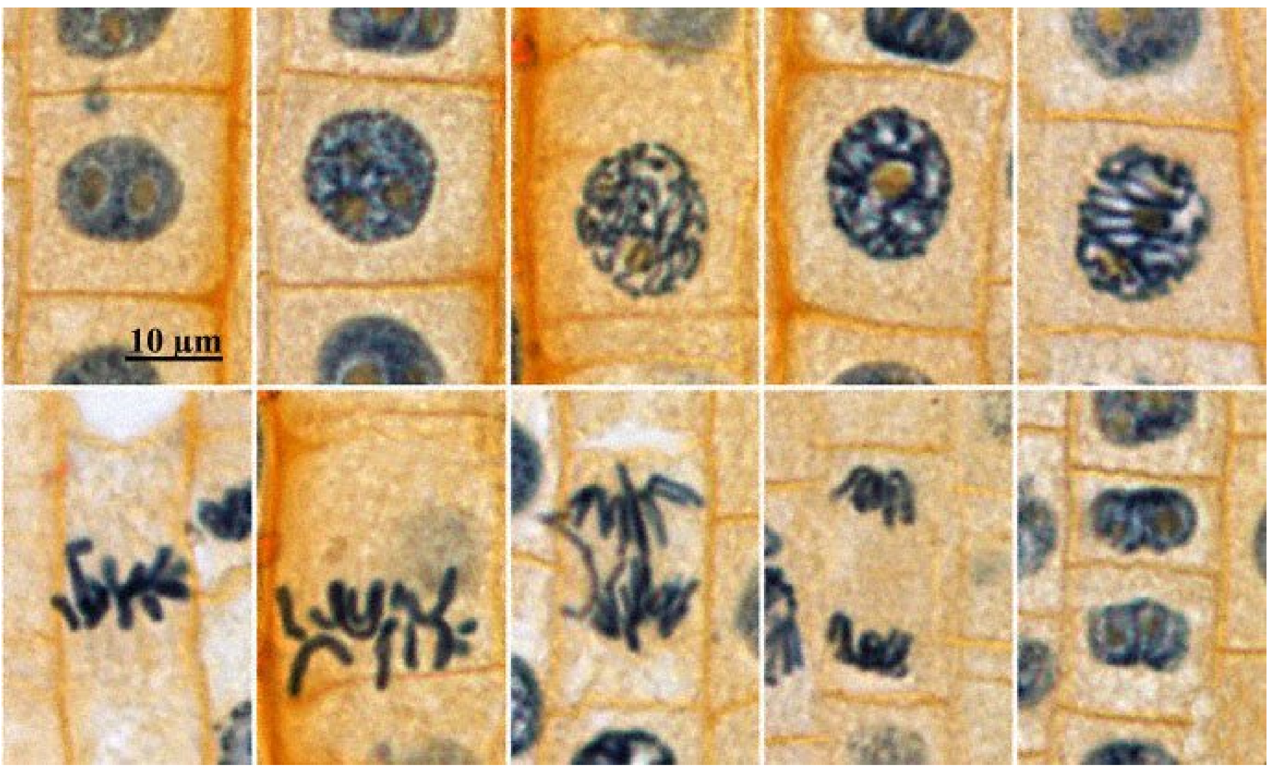
Outline

10 Questions and answers

10.1 Quiz

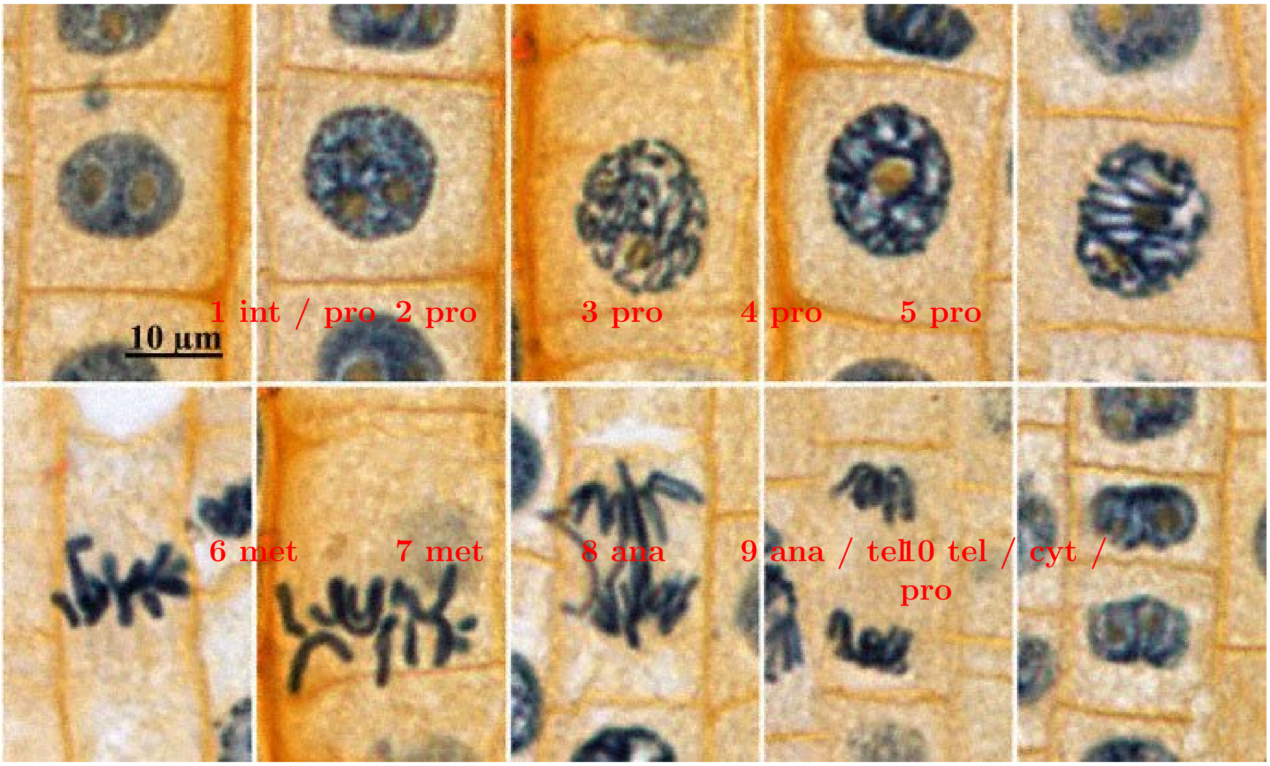
Final question (2 points)

Which stage?



Final question (2 points)

Which stage?



11 Mitosis and meiosis

11.1 Syngamy (Y!)

Why do living things support diversity

- Individual level: diverse genes increase adaptation
- Population level: diverse individuals make population survive

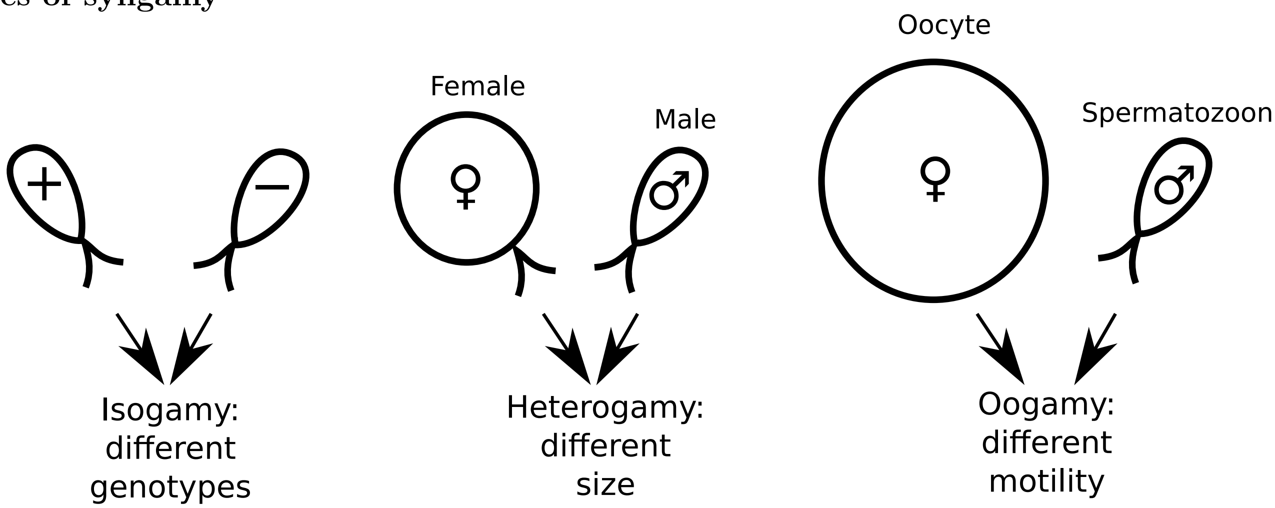
Exchange and renovation of DNA

- To sustain with the ever-changed environment, organisms must evolve ("Red Queen Law")
- To evolve, they need a genetic diversity: different genotypes in different organisms
- To be genetically diverse, they need a process of genetic exchange
- One of ways of exchange is a sexual process in a form of **syngamy**
- However, constant syngamy will result in constant increase of DNA amount
- Meiosis is a counterbalance to syngamy

Definition of syngamy

- *Fusion of two cells, where resulted cell will have two times more chromosomes*
- Initial cells are **gametes**, resulted cell is a **zygote**
- Chromosome formula: X + X $\longrightarrow$ XX
- **The goal of syngamy** is the renovation of genetic material
- Syngamy changes genotype of cells

Types of syngamy



11.2 Meiosis (R!)

Some useful terms: checklist

- Gene
- Protein
- Enzyme
- Genotype
- Phenotype
- Genome
- Population
- Mutation
- Syngamy

Quiz question (... points)

Summary

- **Mitosis** is a equal division of DNA, ploidy does not change, genotype does not change
- **Syngamy** is a sexual process of cell fusion, ploidy doubles, genotype changes
- **Meiosis** is a process of reduction of DNA amount, ploidy halves, genotype changes

For Further Reading

References

[1] A. Shipunov. *Introduction to Botany* [Electronic resource]. Mode of access: `http://ashipunov.info/shipunov/school/biol_154`

Outline

12 Questions and answers

12.1 Quiz

Quiz question (... points)

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-

13 Life cycle

13.1 Syngamy and meiosis

Some useful terms: checklist

- Gene
- Protein
- Enzyme
- Genotype
- Phenotype
- Genome
- Population
- Mutation
- Syngamy

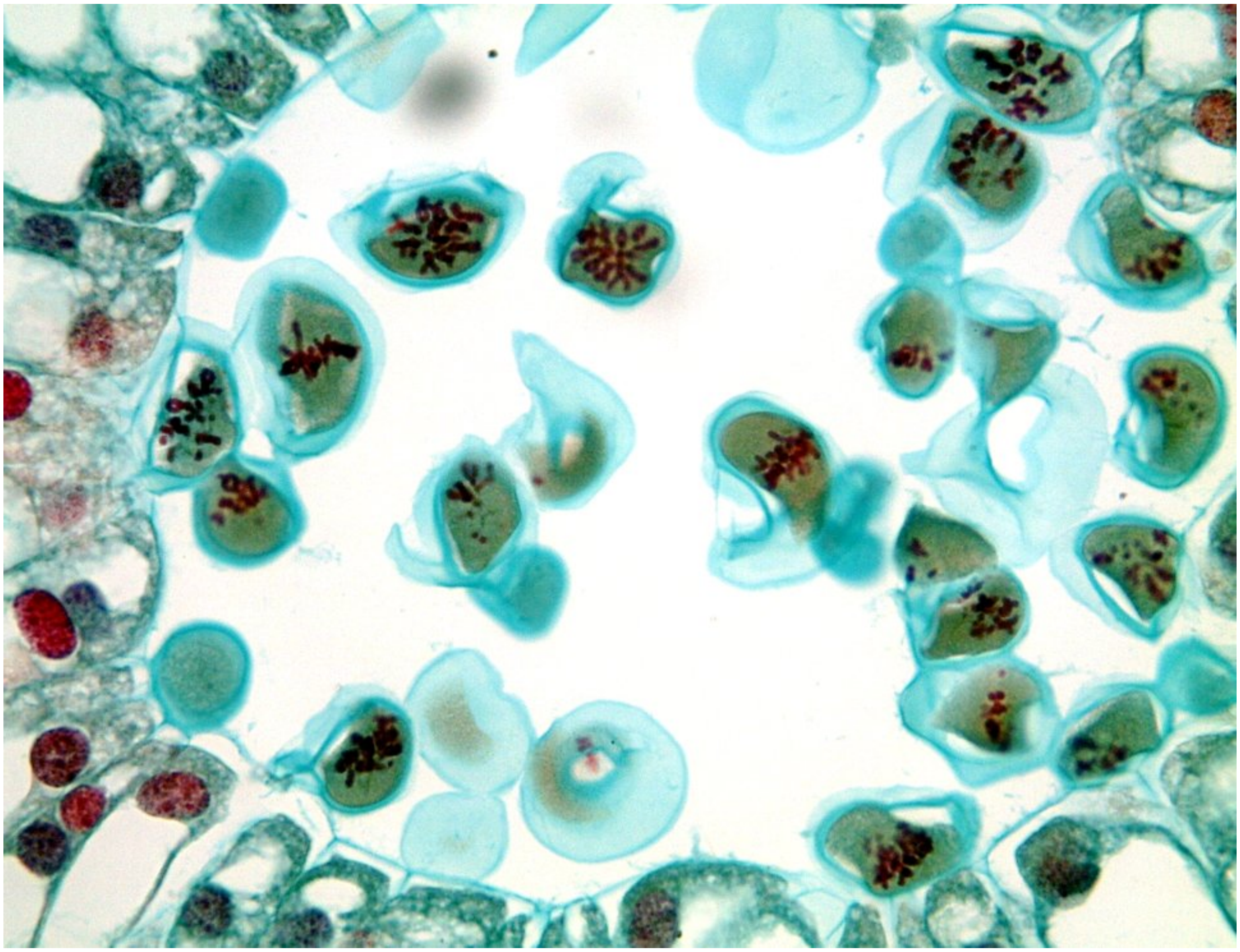
Ploidy, or chromosome set

- In diploid ($2n$) organisms, chromosomes form pairs
- Paired chromosomes (XX) are **homologous**
- In haploid (n) organisms, all chromosomes are single
- In mitosis, ploidy will be the same: $2n \longrightarrow 2n + 2n$
- In syngamy, ploidy will increase: $n + n \longrightarrow 2n$
- In meiosis, ploidy will reduce: $2n \longrightarrow n + n$

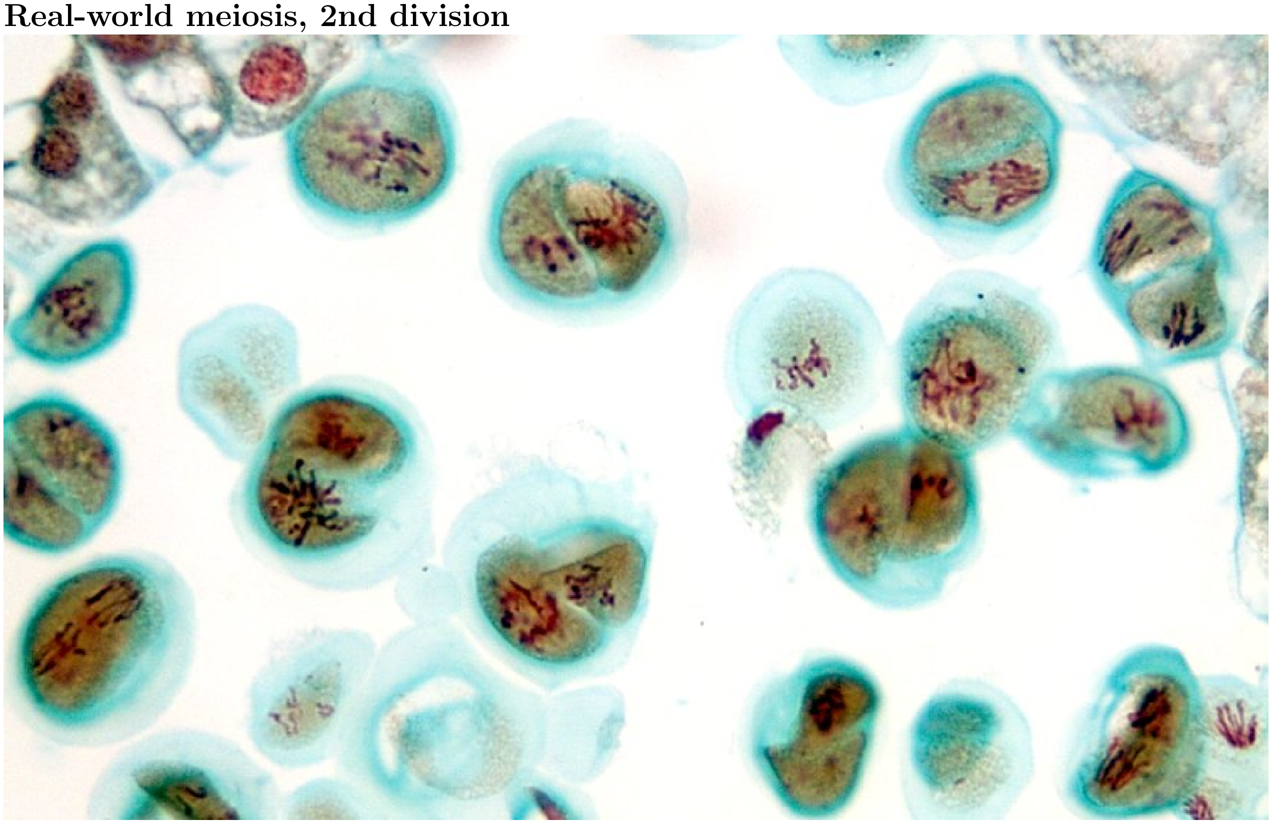
Stages of meiosis

- First division: reductive part
  - Prophase I: homologous chromosomes form pairs (**synapses**) and start to exchange DNA (**crossing-over**)
  - Metaphase I
  - Anaphase I: homologous chromosomes will go *independently* to different poles
  - Telophase I becomes Prophase II, without interphase (and typically without cytokinesis)
- Second division: equal part (similar to mitosis)
  - Prophase II
  - Metaphase II
  - Anaphase II
  - Telophase II

Real-world meiosis, 1st division



Real-world meiosis, 2nd division

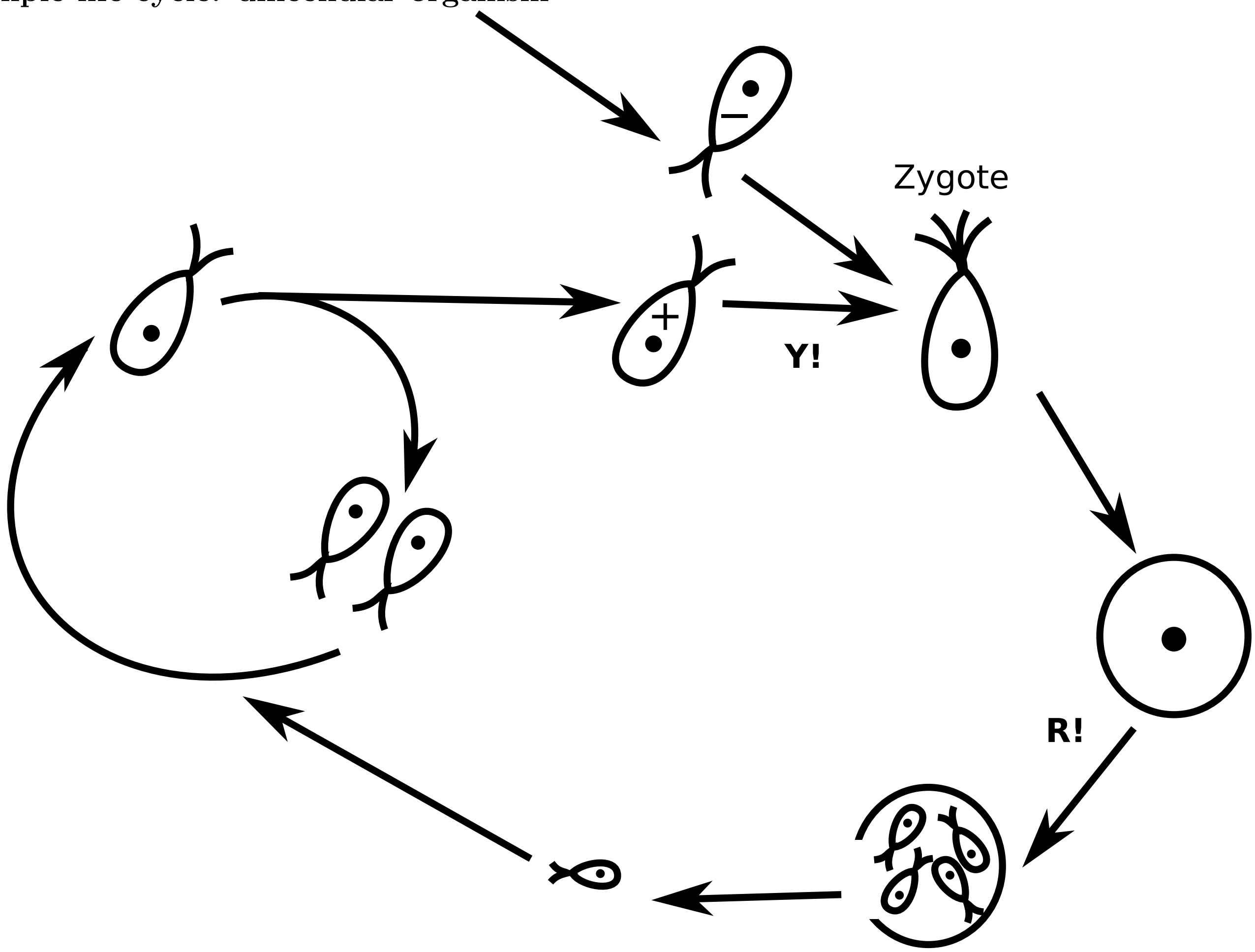


Polyploids

- If for some reason, meiosis will not run correctly, one of resulted cells could receive double set of chromosomes ($2n$ instead of n)
- If this cell goes to syngamy, resulted zygote will have $3n$ chromosomes
- Cells with $> 2n$ chromosomes are **polyploids**

13.2 Basics of life cycles

Simple life cycle: unicellular organism



Summary

- **Mitosis** is a equal division of DNA, ploidy does not change, genotype does not change
- **Syngamy** is a sexual process of cell fusion, ploidy doubles, genotype changes
- **Meiosis** is a process of reduction of DNA amount, ploidy halves, genotype changes
- Meiosis has two stages: first to reduce ploidy, second to split exact copies of DNA

For Further Reading

References

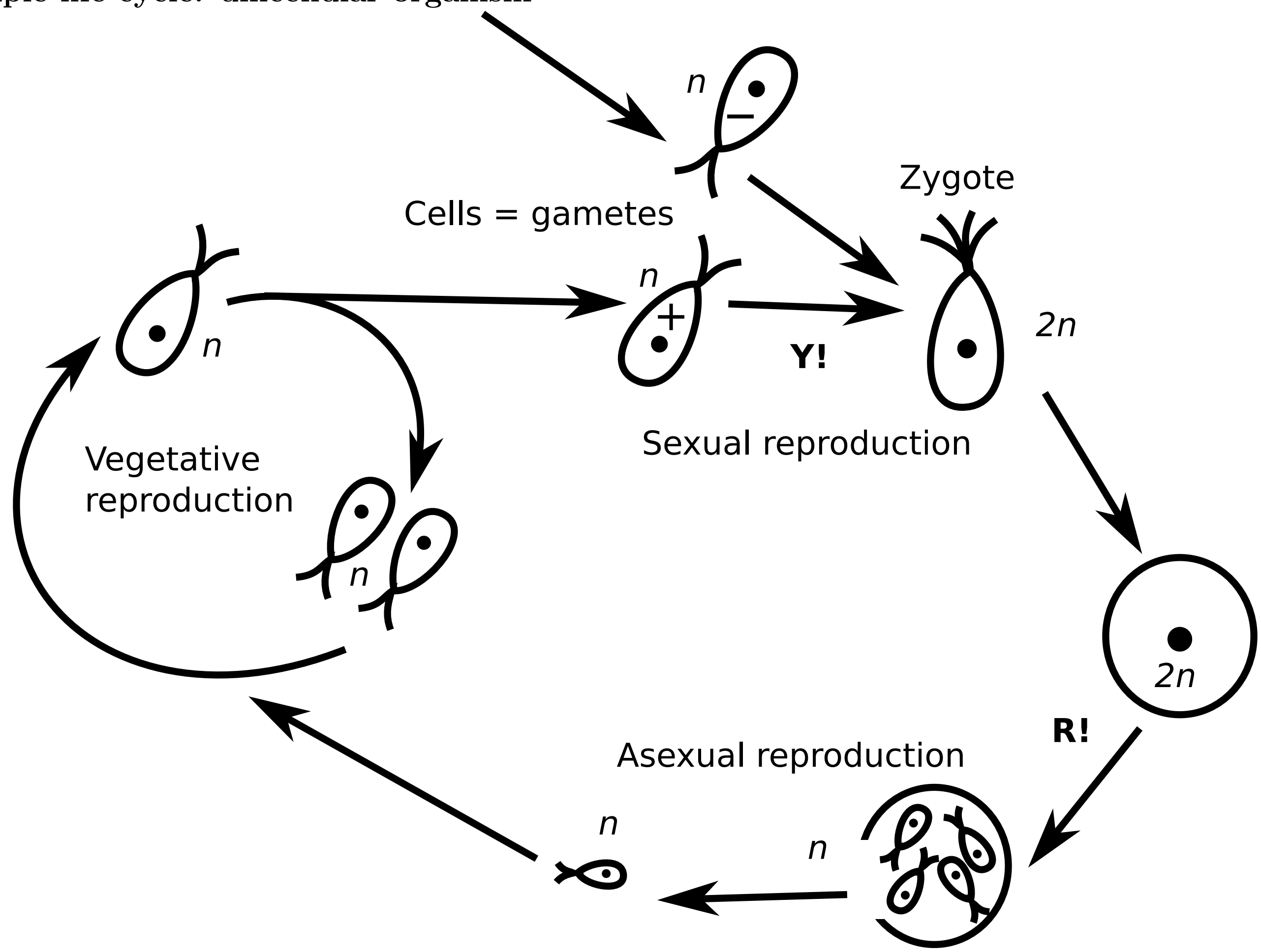
[1] A. Shipunov. *Introduction to Botany* [Electronic resource]. Mode of access: `http://ashipunov.info/shipunov/school/biol_154`

Outline

14 Life cycle

14.1 Basics of life cycles

Simple life cycle: unicellular organism

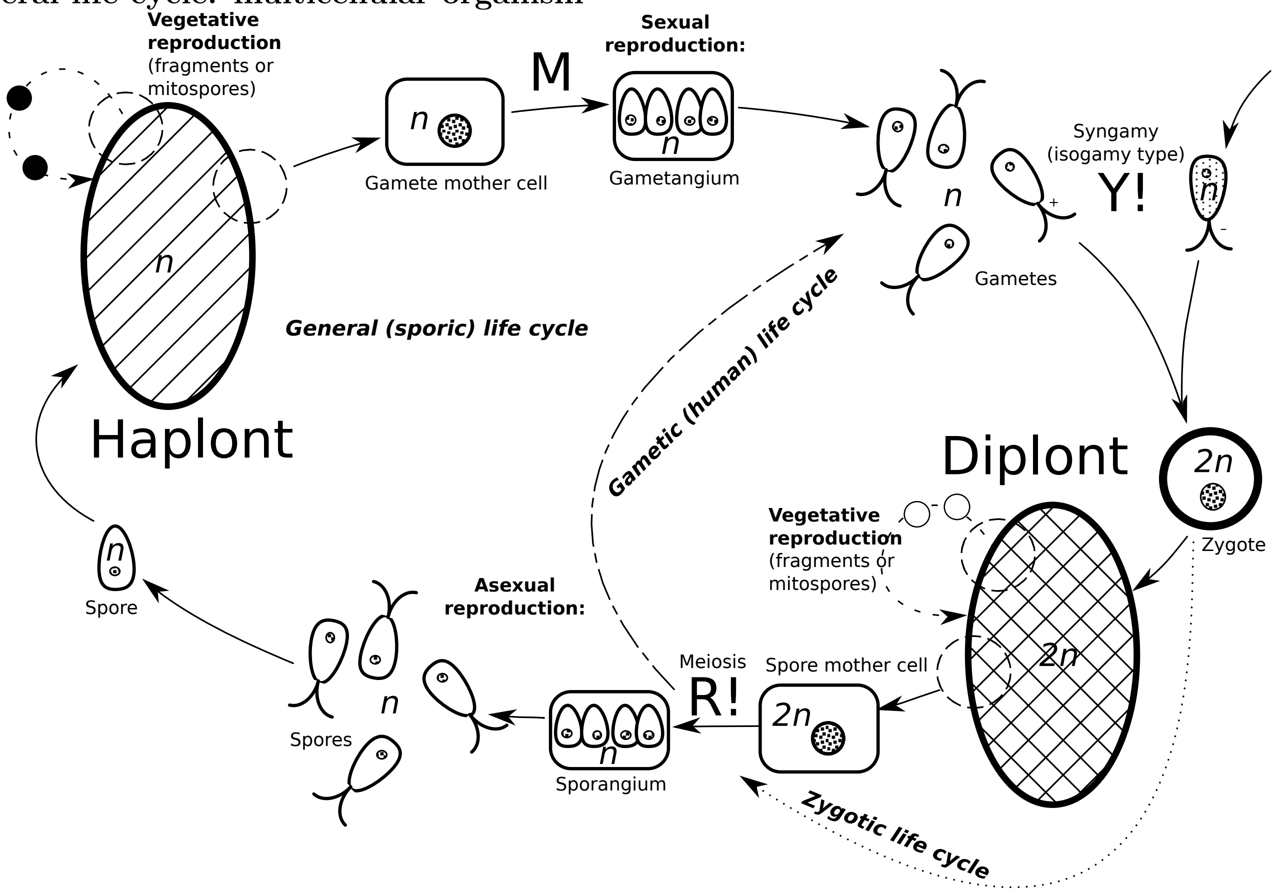


Associated terms: mitosis, meiosis (R!), syngamy (Y!), reproduction, sexual reproduction, asexual reproduction, vegetative reproduction, isogamy, heterogamy, oogamy, zygote, gamete, male, female, spermatozoon, oocyte

Multicellularity, or Origin of Death

- Sometimes, cells do not part after mitosis. These simple cell aggregates may benefit from their size (e.g., harder to swallow) and putative division of labor (e.g., capture light from different sides and share products of photosynthesis)
- Next step is to separate *germ cells* and *somatic cells*. Somatic cells with eventually die whereas germ cells may give an offspring.
- This is the beginning of **multicellularity**.
- Life cycles of multicellular organisms are based on interleaving **haplont** and **diplont**, the second is making **spores**

General life cycle: multicellular organism



Quiz question (... points)

Summary

- **Mitosis** is a equal division of DNA, ploidy does not change, genotype does not change
- **Syngamy** is a sexual process of cell fusion, ploidy doubles, genotype changes
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For Further Reading

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Outline

15 Questions and answers

15.1 Quiz

Quiz question (2 points)

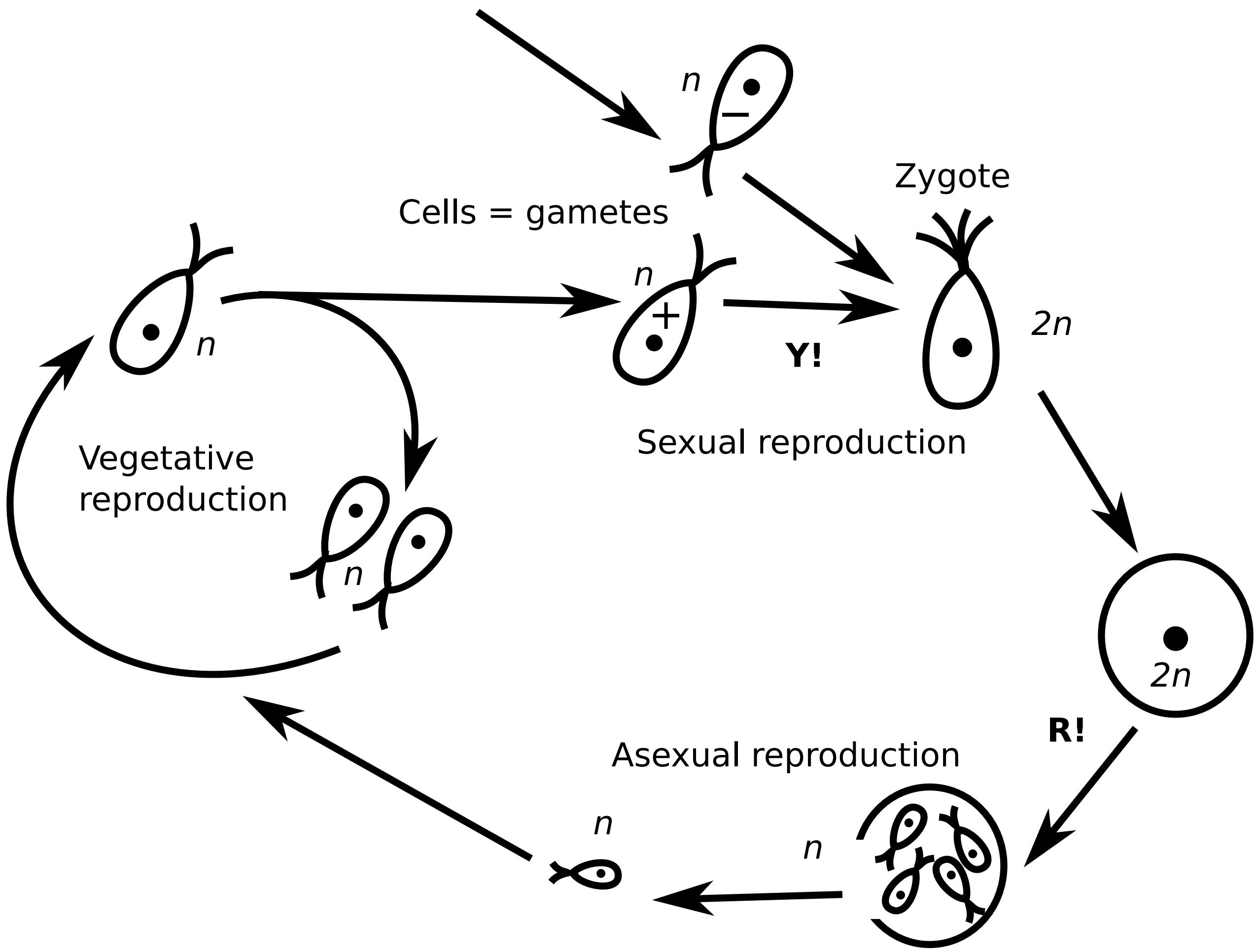
Why is multicellularity better?

- Organism is bigger
- Many cells allow for division of labor

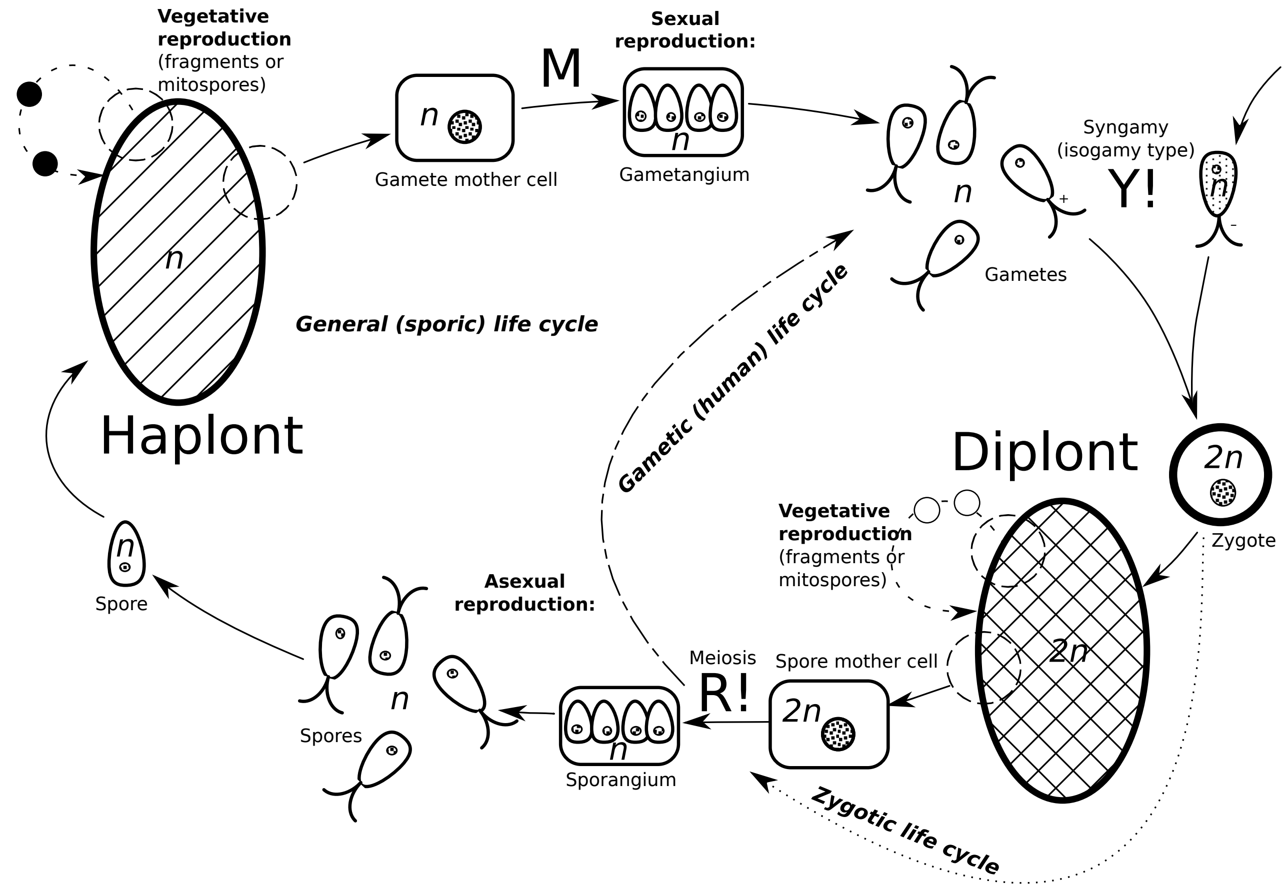
16 Life cycle

16.1 Basics

General life cycle: unicellular organism



General life cycle: multicellular organism

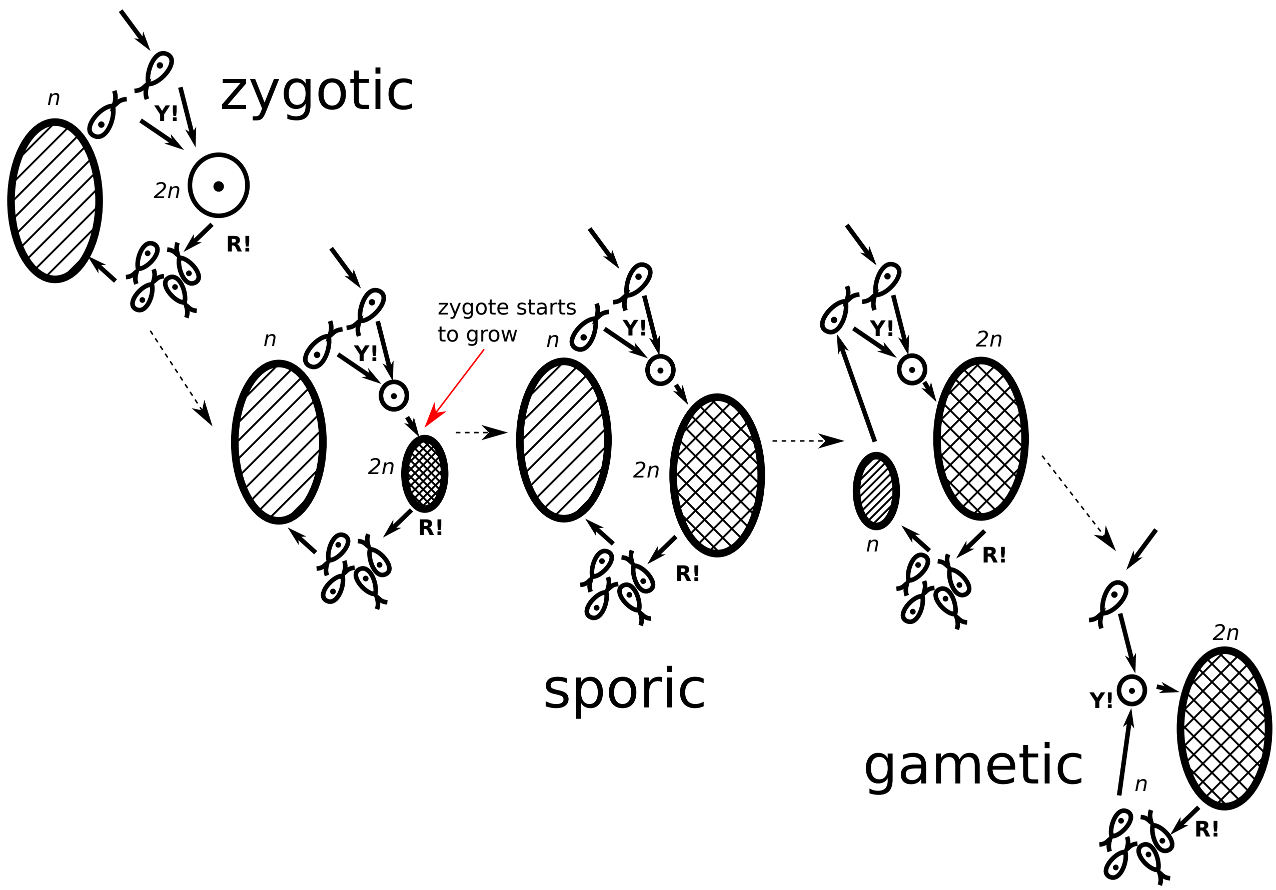


16.2 Evolution of life cycles

3 cycles

- **Zygotic**: Y! → R!, no diplont, many protists
- **Gametic**: R! → Y!, ho haplont, animals and few protists
- **Sporic**: both haplont and diplont, many protists and all plants$_2$

Diplonts grow, haplonts reduce



Why diplonts are better?

They have two variants of each gene!

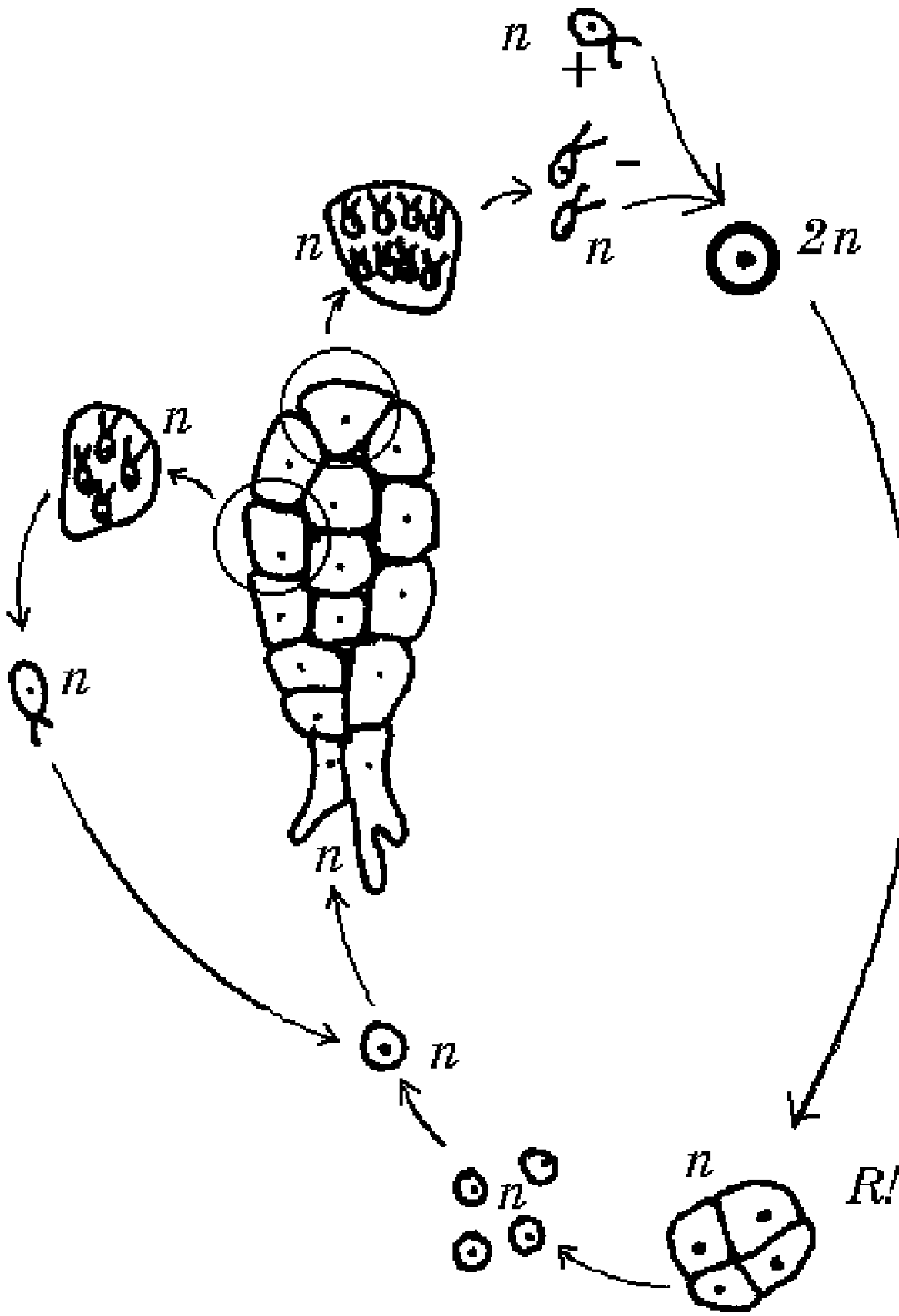
A. **Dominance**: if one gene is deadly mutated, there is the second working variant

B. **Protein production**: two genes will give more protein

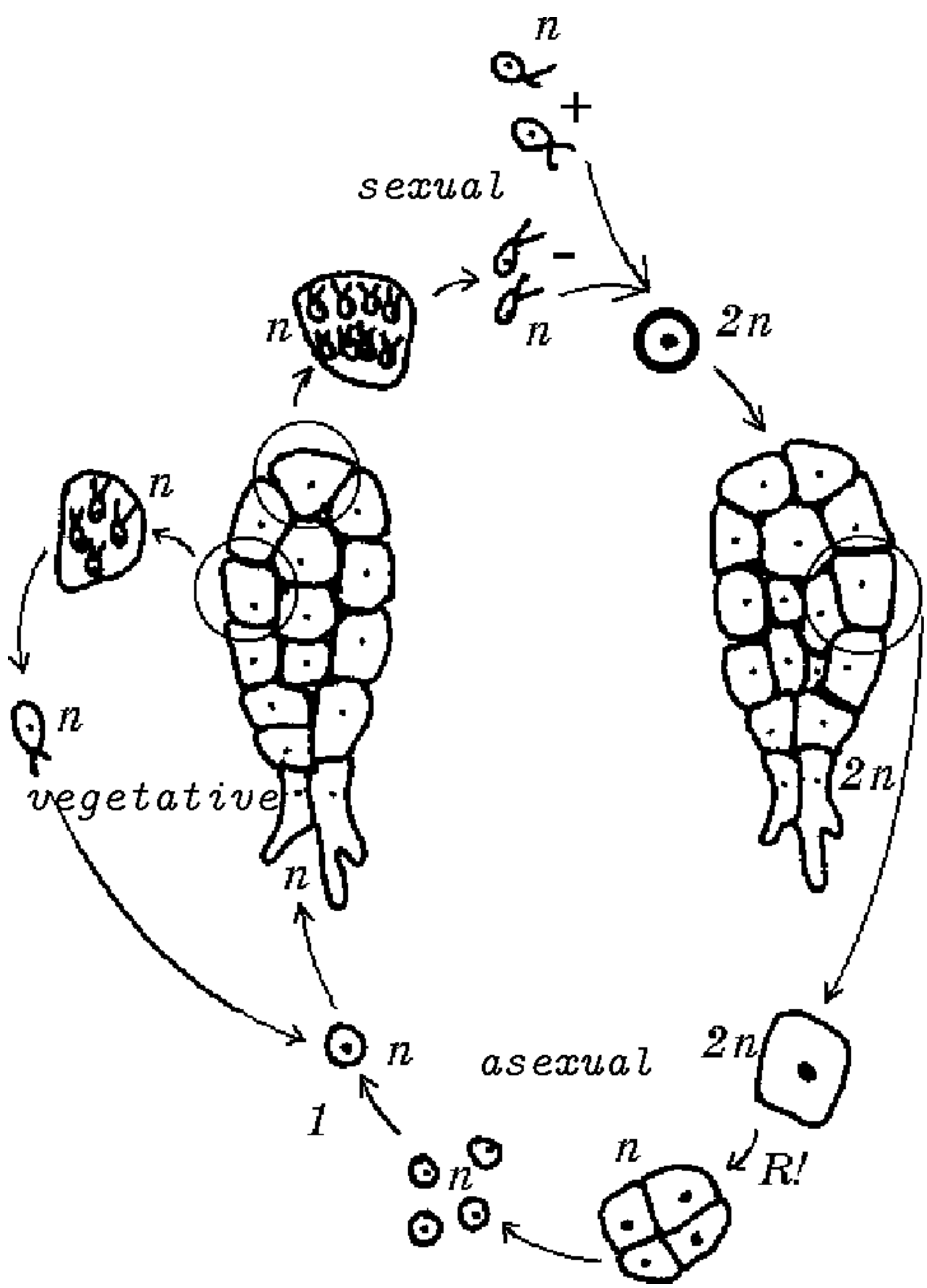
C. **Diversity**: if one gene is producing protein adapted to +5...+30°C and other—to +10...+35°C, the organism may live under +5...+35°C

16.3 Diversity of life cycles

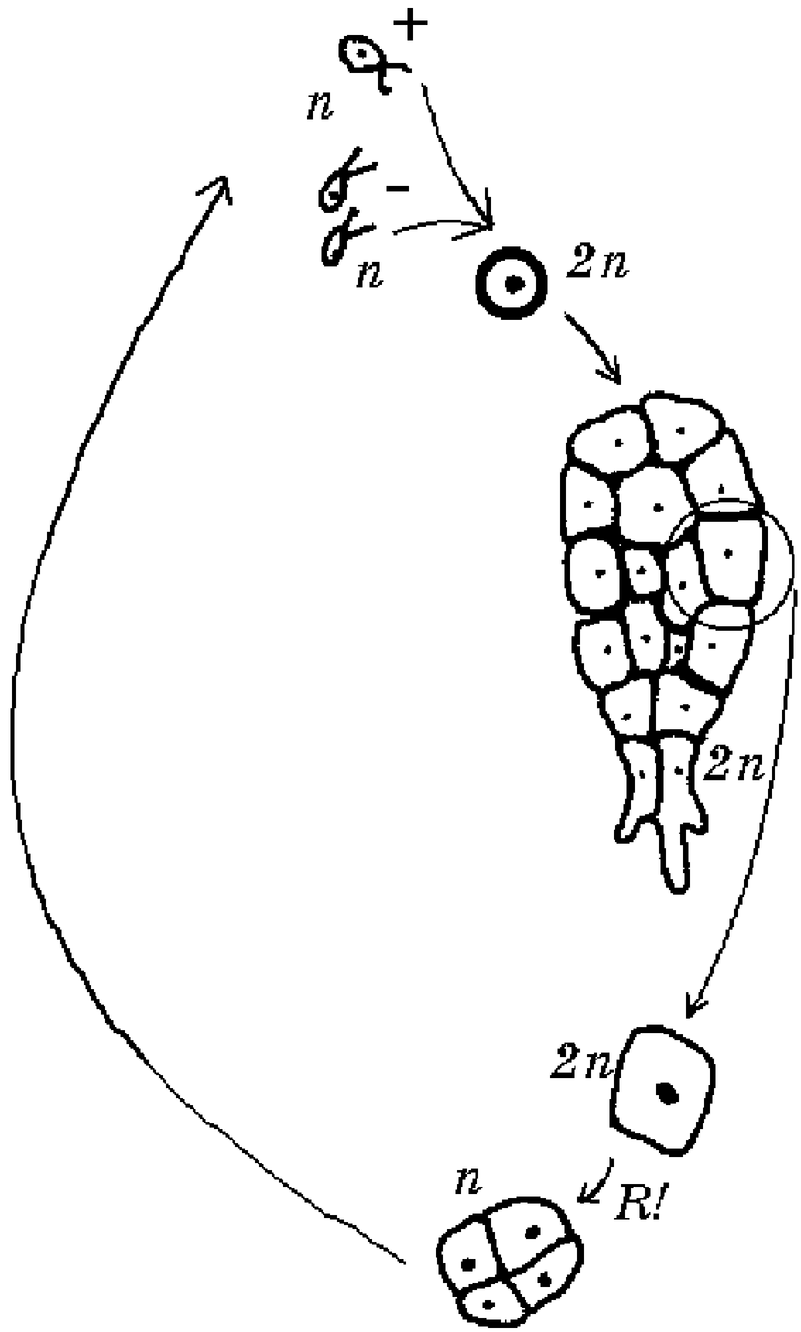
Zygotic life cycle: protists



Sporic life cycle: plants



Gametic life cycle: animals

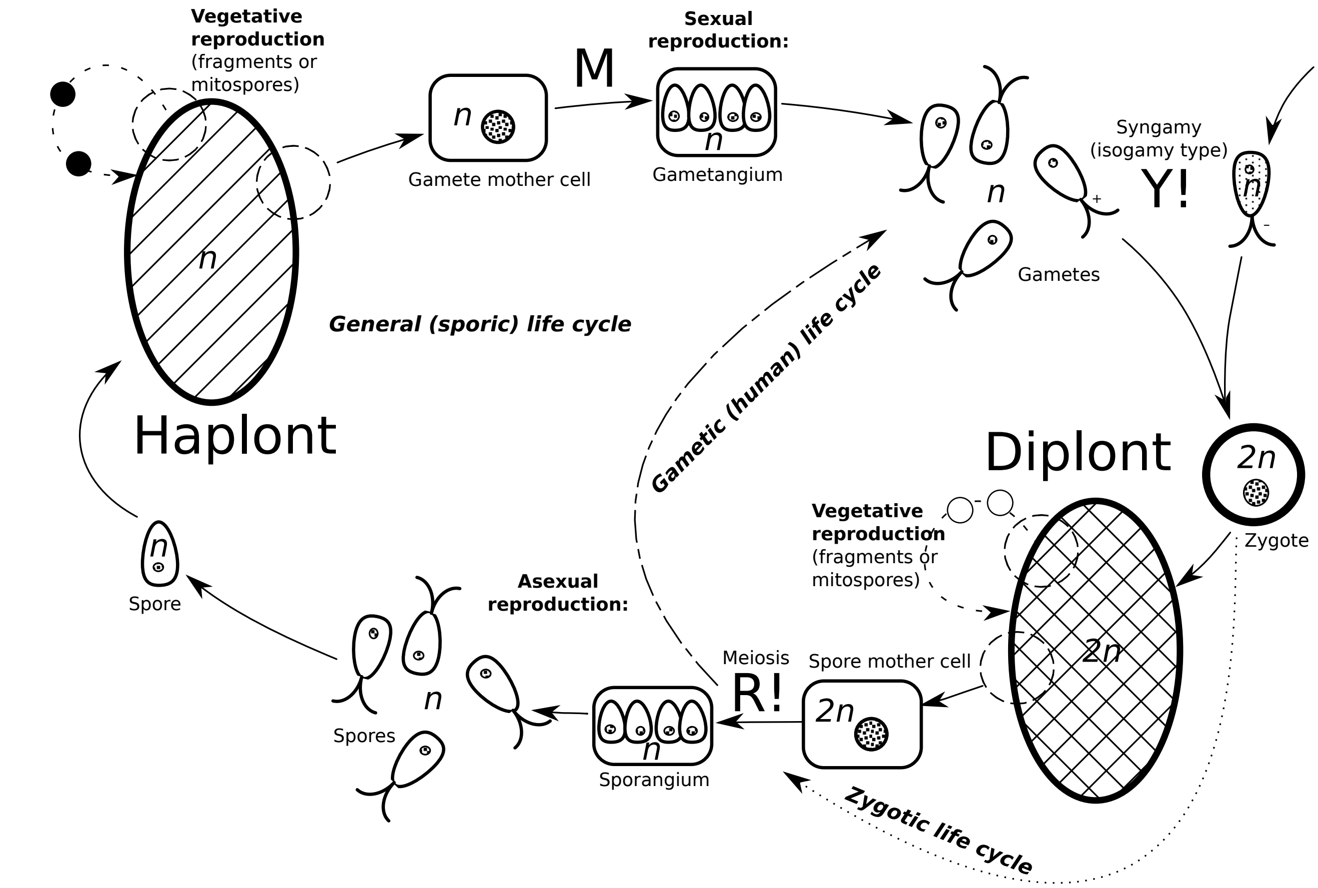


Life cycle math

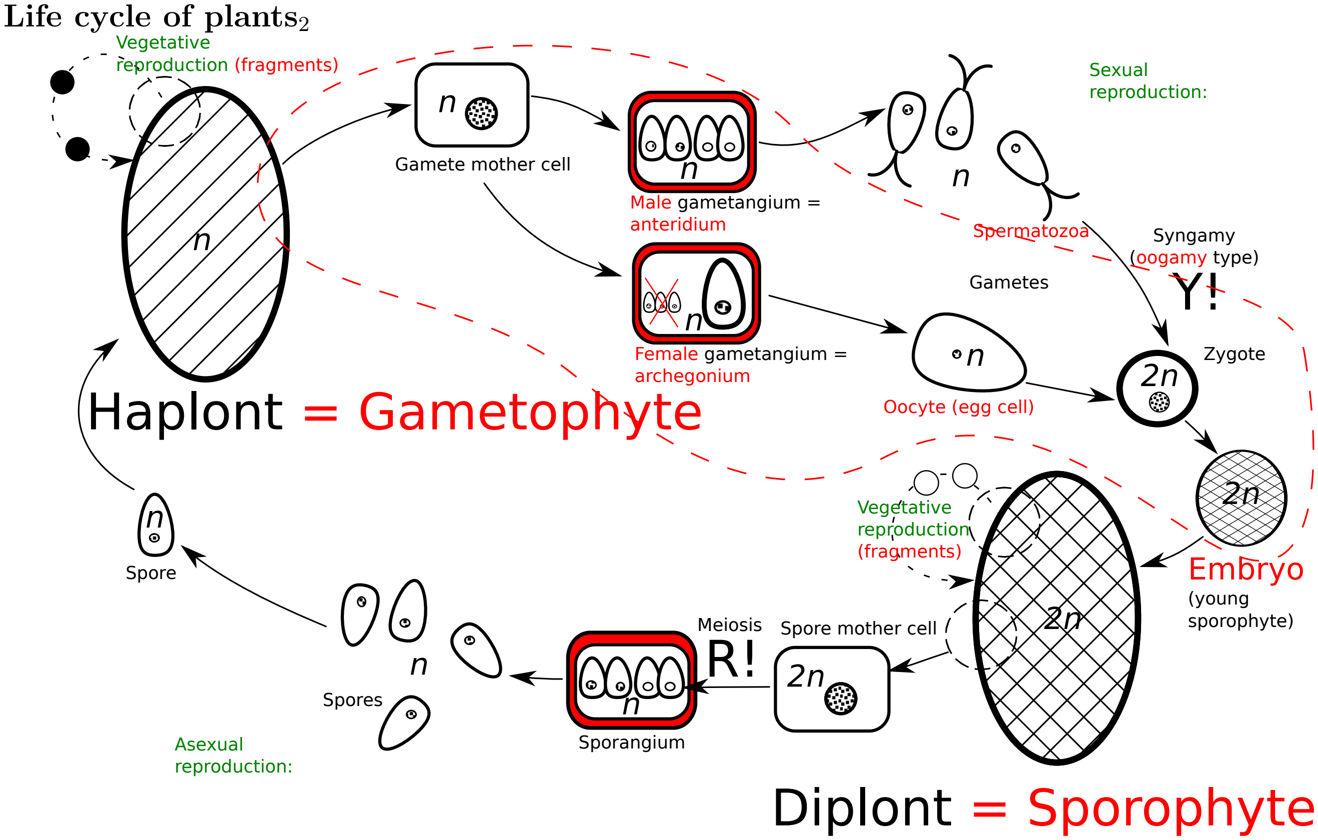
$$
\begin{tikzcd}
n_i \arrow[r] & \begin{array}{c}\text{Sexual reproduction}\\ \text{Syngamy (Y!)}\end{array} \arrow[r] \arrow[ddd, dashed, shift left=3ex, "1"] & 2n_1 \arrow[d] \\
\vdots \arrow[u] & & 2n_2 \arrow[d] \\
n_2 \arrow[u] & & \vdots \arrow[d] \\
n_1 \arrow[u] & \begin{array}{c}\text{Meiosis (R!)}\\ \text{Asexual reproduction}\end{array} \arrow[l] \arrow[uuu, dashed, shift left=3ex, "2"'] & 2n_k \arrow[l]
\end{tikzcd}
$$

1 — zygotic cycle (Y!→R!);
2 — gametic cycle (R!→Y!).

Life cycle (again)



Life cycle of plants$_2$



Quiz question (2 points)

...

Summary

- **Zygotic** life cycle has no *diplont*, **gametic** life cycle has no *haplont*, **sporic** life cycle has both *haplont* and *diplont*
- The evolution of life cycles goes from zygotic to sporic and then to gametic because "diplonts are better"

For Further Reading

References

[1] A. Shipunov. *Introduction to Botany* [Electronic resource]. Mode of access: http://ashipunov.info/shipunov/school/biol_154

17 Movie

David Attenborough. Private Life of Plants. Episode 5: Living Together. https://en.wikipedia.org/wiki/The_Private_Life_of_Plants