Introduction to Botany: BIOL 154
Study guide

Alexey Shipunov

Lectures

Contents

Outline

Help in greenhouse?

Volunteers to help on Friday, August 31st, 3pm?

1 Intro test

1.1 Multiple choice questions

Question 1

1 Why do our deciduous plants drop their leaves?

A. To prevent freezing
B. To prevent desiccation
C. To prevent sunburns

Question 2

2 Where does human digestion process start?

A. In the mouth
B. In the intestines
C. In the stomach

Question 3

3 Which birds do NOT live in Minot on winter?

A. Crows

B. Hummingbirds

C. Sparrows

Question 4

4 Home country of watermelon:

A. Central America

B. Canada

C. South Africa

Question 5

5 Why do insectivorous plants eat insects?

A. To obtain the lacking mineral resources

B. To get an addition to their common “menu”

C. To get rid of herbivores

Question 6

6 Which insects have no queen?

A. Bumblebees

B. Ants

C. Cockroaches

Question 7

7 Oak tree is pollinated by:

A. Wind

B. Bees

C. Flies

Question 8

8 Spider has:

A. 6 legs

B. 8 legs

C. 4 legs

Question 9

9 Apple flower has:

A. 5 petals
B. 4 petals
C. 3 petals

Question 10

10 Frightened man has:

A. Bigger pupils
B. Smaller pupils
C. Normal pupils

Question 11

11 Polar bears are not eating penguins because:

A. Penguins run very fast
B. They cannot meet
C. Penguins are poisonous for bears

Question 12

12 How many toes are on each of cat's hind legs?

A. 5
B. 4
C. 3

Question 13

13 Pineapple is a:

A. Tree
B. Shrub
C. Herb

Question 14

14 If somebody has an artery cut on the arm or leg, it is recommended:

A. Put a tight bandage below the cut
B. Put a tight bandage above the cut
C. Do nothing

Question 15

15 Which of the following is the most precise statement?

A. We are breathing to support our life
B. We are breathing to obtain the energy from food
C. We are breathing to have enough strength for food consuming

Question 16

16 Which tree is better to plant in Minot house backyard:

A. Sycamore
B. Ash
C. Yew

Question 17

17 Moles eat:

A. Worms
B. Roots
C. Frogs

Question 18

18 Which fish gives birth to the fully developed offspring?

A. Sturgeon
B. Shark
C. Flounder

Question 19

19 Which human organ lives longer?

A. Heart
B. Lungs
C. Brains

Question 20

20 Which plant normally has a longer root?

A. Spruce
B. Chokecherry
C. Blueberry

The key

1B; 2A; 3B; 4C; 5A; 6C; 7A; 8B; 9A; 10A; 11B; 12B; 13C; 14B; 15B; 16B; 17A; 18B; 19A; 20B

Please calculate a sum (every right answer = 1 virtual point)

1.2 Comments to introductory test

Question 1

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B. **To prevent desiccation**
C. To prevent sunburns

Question 2

2 Where does human digestion process start?

A. **In the mouth**
B. In the intestines
C. In the stomach

Amylase and *lipase*

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3 Which birds do NOT live in Minot on winter?

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Bumblebees

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Oak flowers

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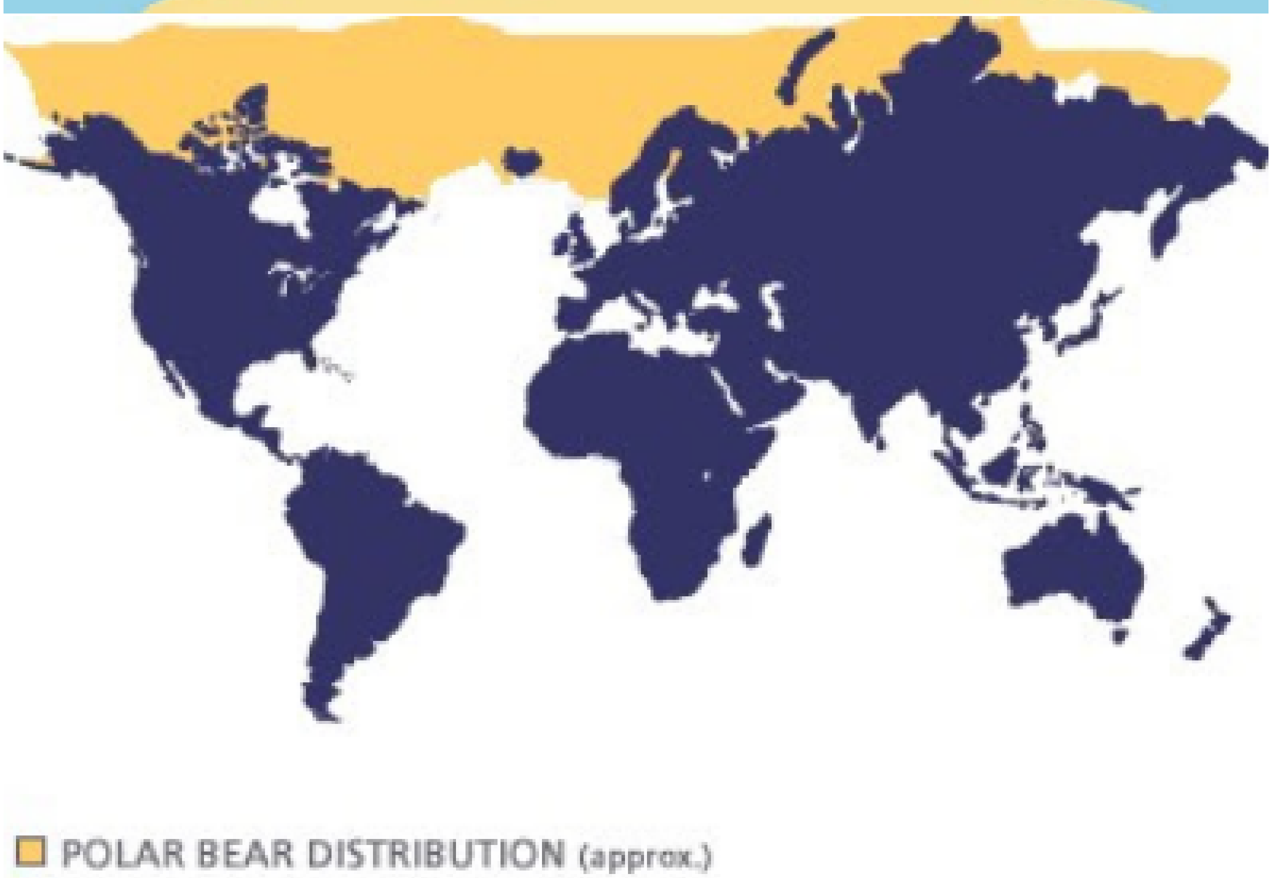

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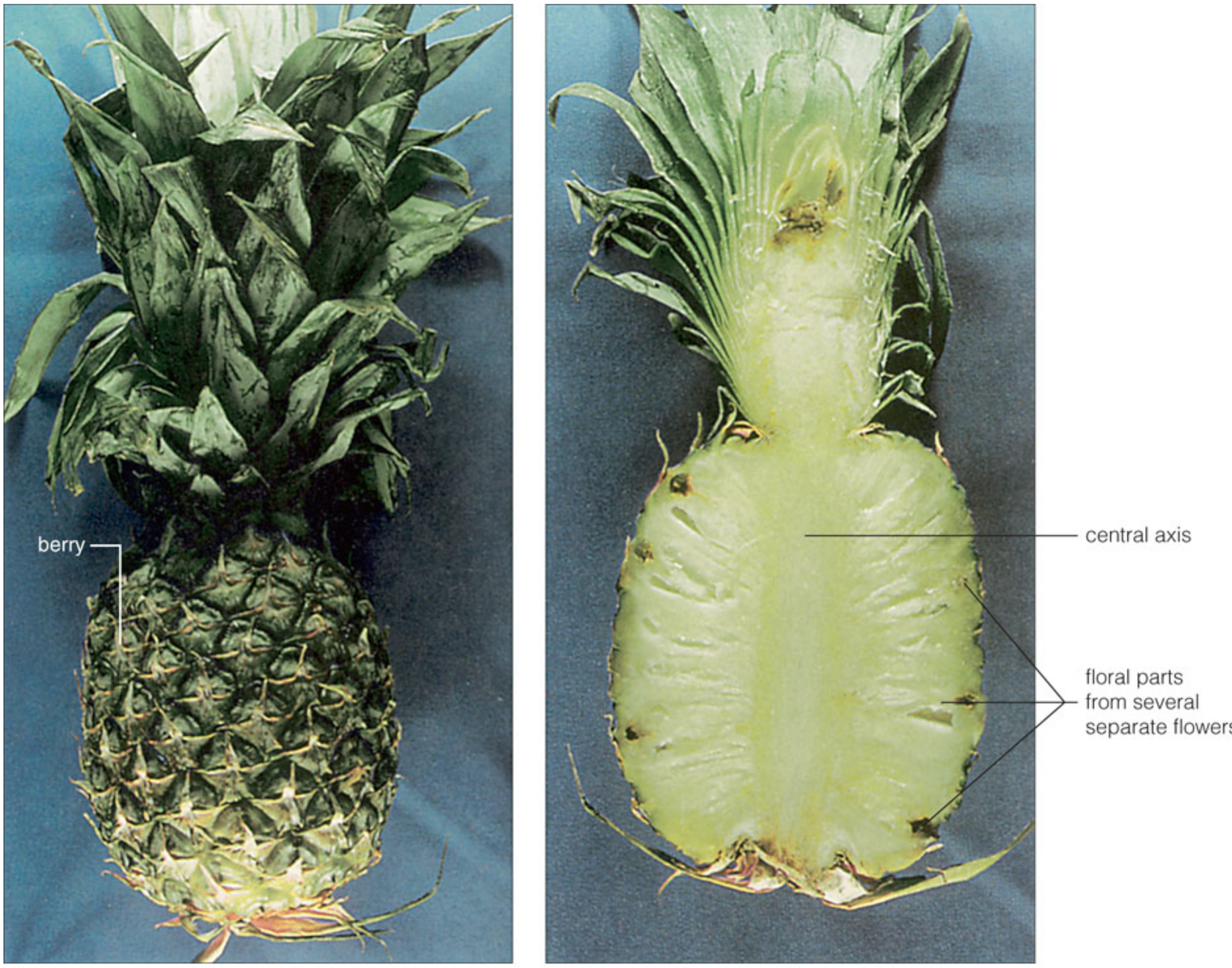

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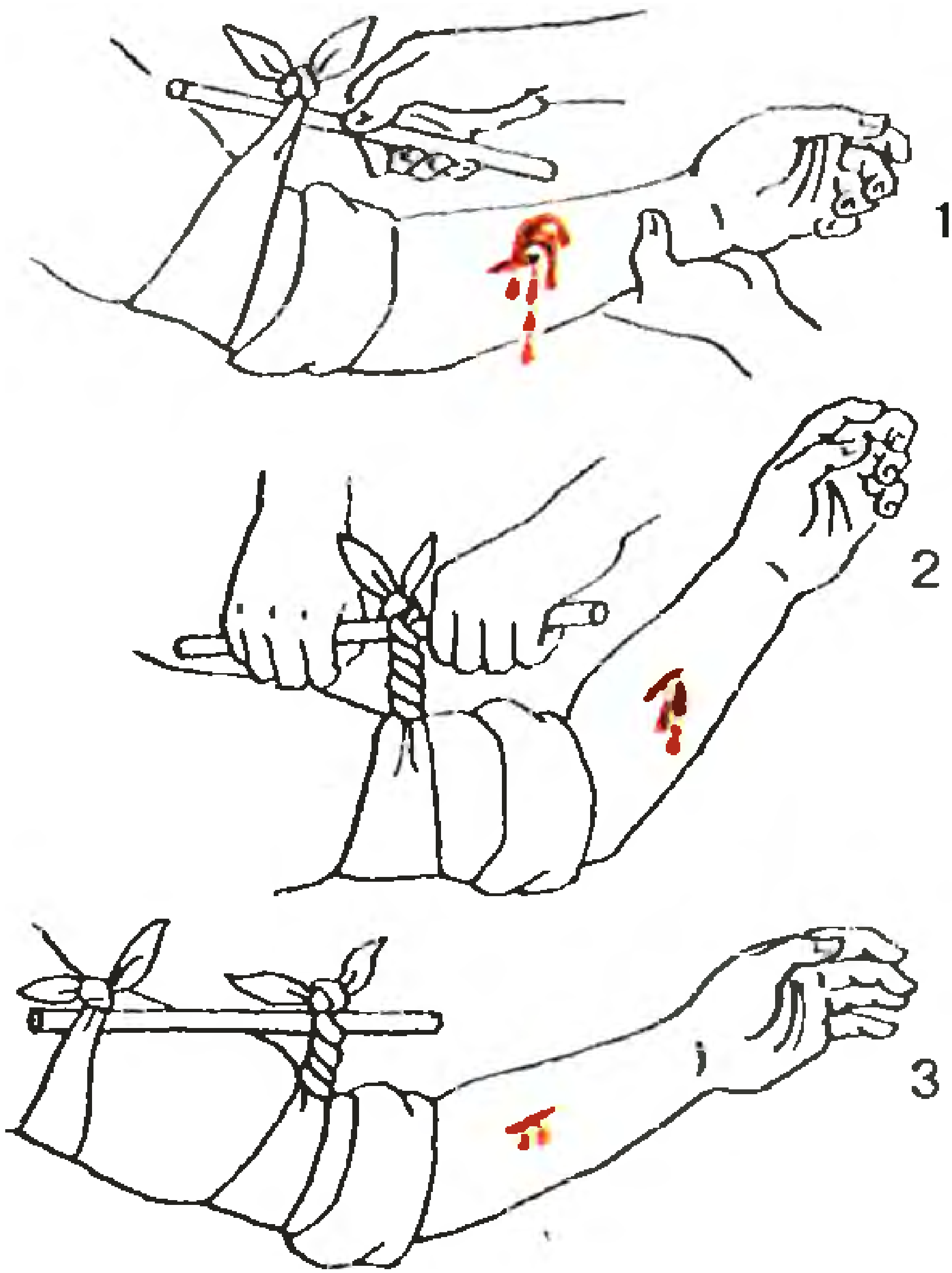

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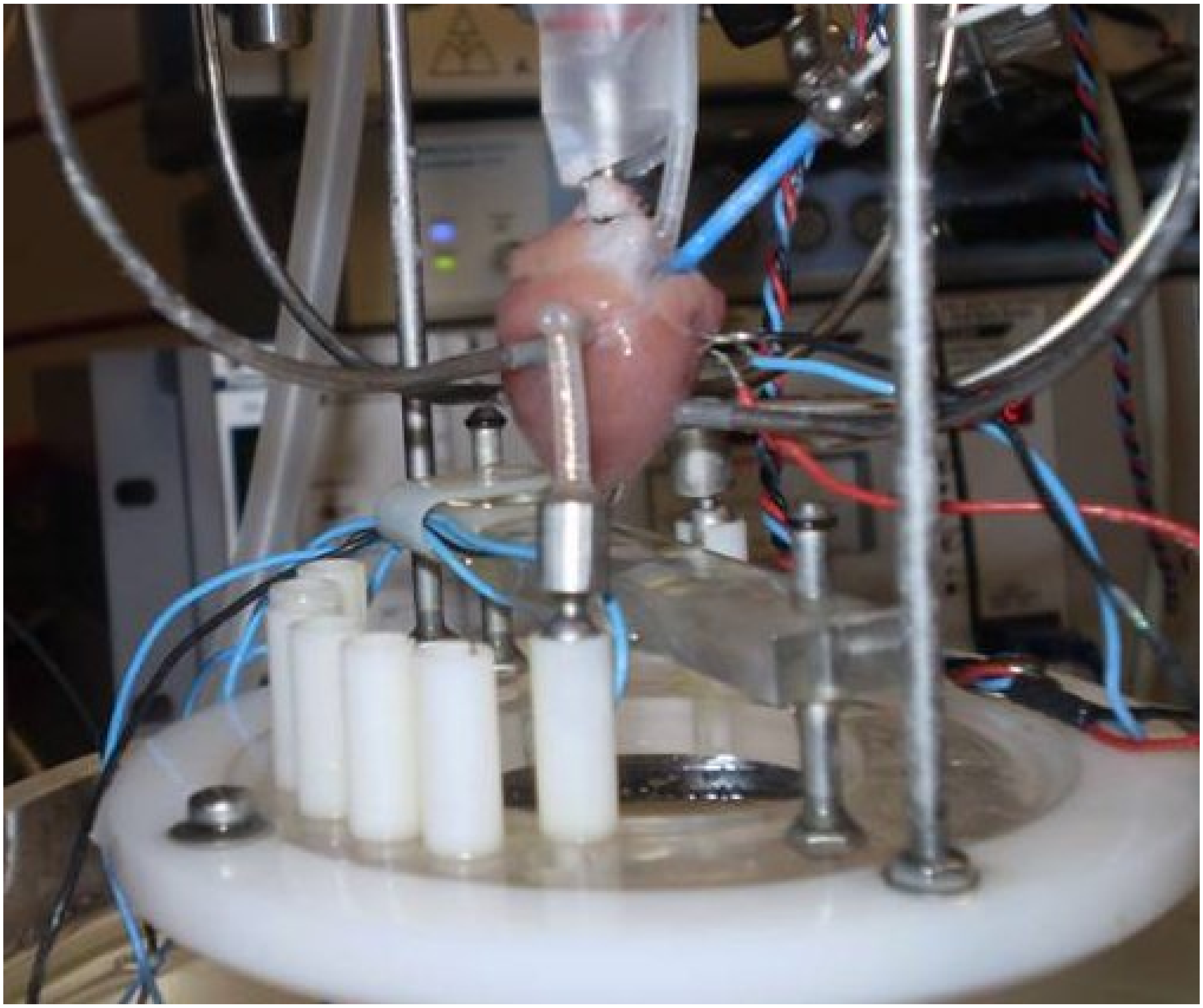


Question 20

20 Which plant normally has a longer root?

A. Spruce
B. **Chokecherry**
C. Blueberry

Fallen spruce tree

2 Importance of Plants

2.1 Class discussion

Importance of plants

Why are plants important?

Final question (1 point)

Why are plants important?

Summary

- BIOL 154: download (and read!) the syllabus from the Web site (`http://ashipunov.info/shipunov/school/biol_154/`)
- Plant is not an animal!
- Plants are extremely important, highly diverse and deserve a scientific study

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

Importance of plants

Why are plants important?

- Food
- Oxygen
- ...?

[aesthetics, landscape, materials, drugs,...]

4 Plants: definition

4.1 Plants$_1$ and plants$_2$

Plants$_1$ and plants$_2$

- Plants$_1$ are all green photosynthetic organisms
- Plants$_2$ are "typical plants" (better definition follows)

The nature of two definitions

- Plants$_1$—ecological definition (based on the role in nature)
- Plants$_2$—taxonomic definition (based on the evolution)

Plants$_1$ is about ecology

Plants$_1$ are *photosynthetic organisms*:

$$H_2O + CO_2 + \text{light} \rightarrow \text{organic compounds} + O_2$$

Some plants$_1$ could taxonomically be bacteria or even animals!

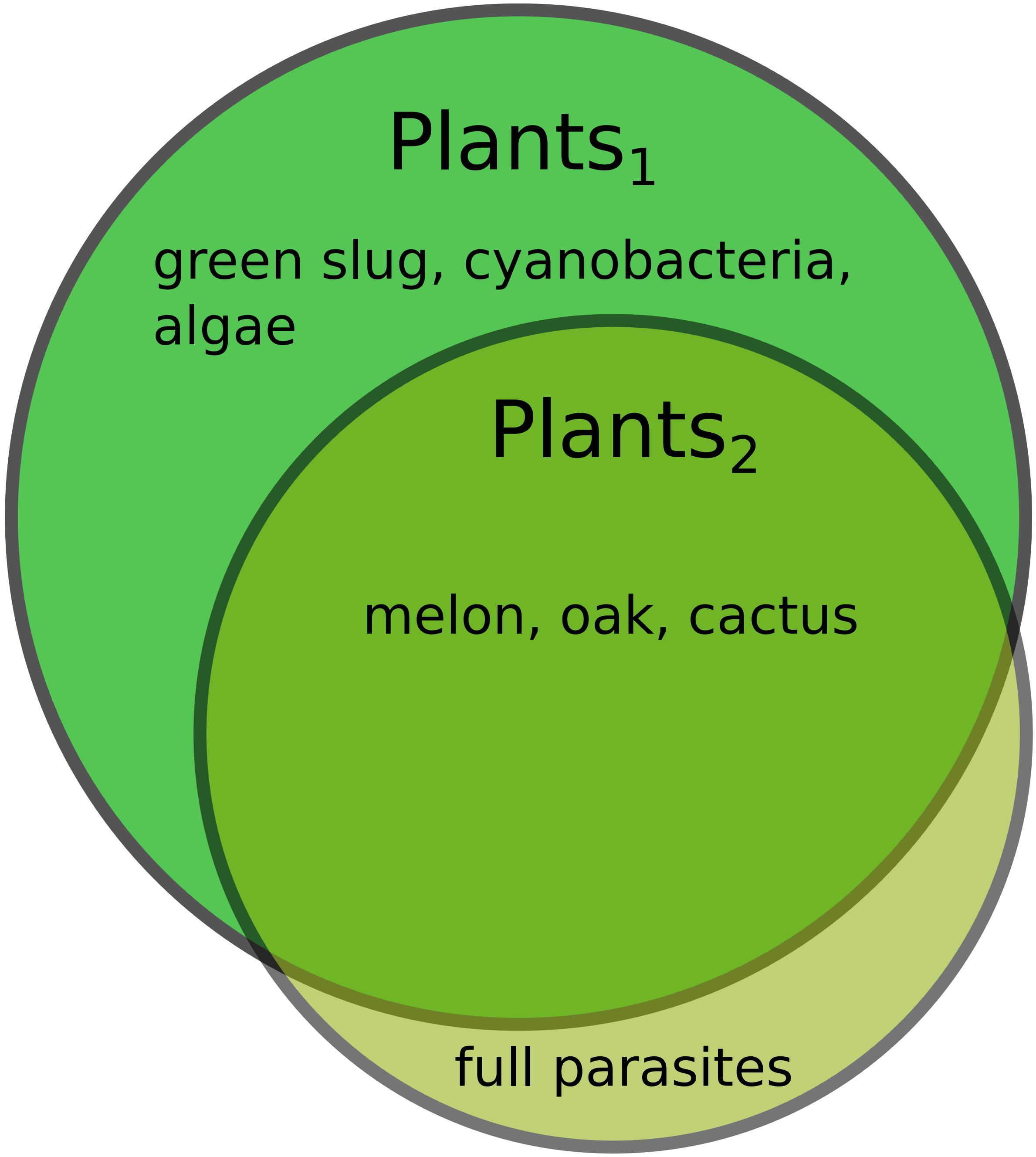
Green slugs


Green slugs obtain chloroplasts from algae, but keep them all their life, feed from them and even use chloroplast genes.

Green *Hydra*

No mouth!

Plants$_1$ and plants$_2$ are similar but not the same


Plants$_1$
green slug, cyanobacteria, algae
Plants$_2$
melon, oak, cactus
full parasites

Hydnora

Root parasite

Pilostyles

Tissue parasite

Dodder

Stem parasite

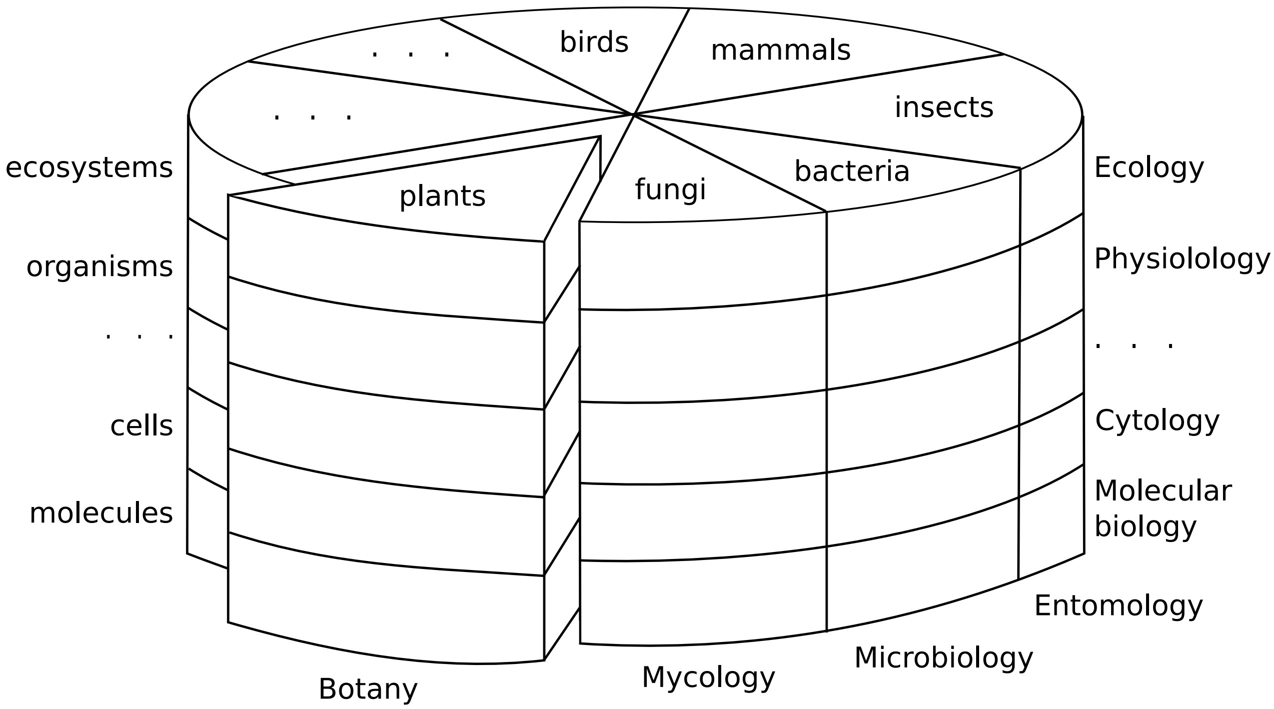
5 Plants in general

5.1 Levels of organization

Levels of organization

- Ecosystems OR Taxa
- Populations
- Organisms
- Organs
- Tissues
- Cells
- Organelles
- Molecules

Place of botany



Layered cake of biology (Odum, 1971): botany is a "slice science"

5.2 Taxonomy

Ranks

Most scientists accept seven main ranks:

- Kingdom
- Phylum
- Class
- Order
- Family
- Genus
- Species

Names

- Names of species are binomials like *Solanum tuberosum* (potato)
- Names of other ranks are uninomials like **Vegetabilia** (plant kingdom)

Plants$_1$ and plants$_2$ (updated)

- Plants$_1$ are all photosynthetic organisms
- Plants$_2$ are **Vegetabilia**: multi-tissued, terrestrial, primarily photosynthetic eukaryotes

Summary

- "Plants" have **two definitions**
- Botany is a "slice" science

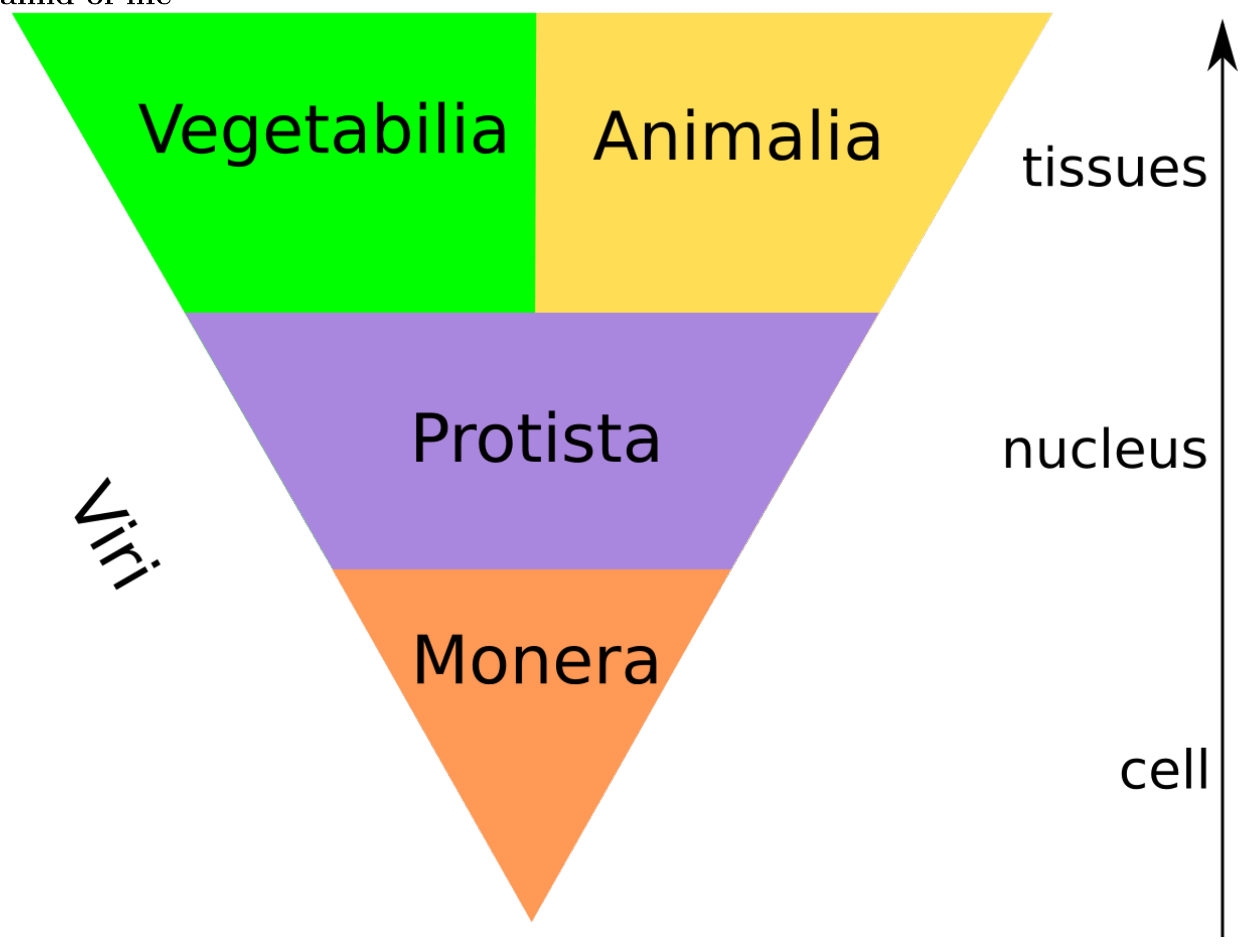
For Further Reading

References

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

Outline

Pyramid of life



Questions about pyramid

What is Monera? Prokaryotes: (1) Bacteria and (2) Archaea

What is Protista? Eukaryotes without tissues

Where are eukaryotes? Protista, Vegetabilia and Animalia

Where are fungi? They belong to different protists

Where are plants$_2$? Vegetabilia

Where are plants$_1$? Here it is not applicable

Why are two groups on one level? Vegetabilia and Animalia both have tissues but obtained them for the radically different purposes. Animals acquired *kinoblast* and *phagocytoblast* **to hunt and digest**, and plants have *epidermis* and *photosynthetic tissue* **to survive on land**.

6 Ways of life

6.1 Energy and food

Ways of life

- How to obtain energy?

  A. From sun light: **phototrophy**

  B. From chemical reactions with inorganic matter ("rocks"): **lithotrophy**

  C. From breaking organic molecules into inorganic (typically, carbon dioxide and water): **organotrophy**

- How to obtain building blocks?

  A. From assimilation of carbon dioxide: **autotrophy**

  B. From other living beings: **heterotrophy**

Six life styles and taxonomy

	Phototrophs	**Lithotrophs**	**Organotrophs**
Autotrophs	Plants$_1$: some Monera, some Protista, most of Vegetabilia	Some Monera	Some Monera
Heterotrophs	Some Monera	Some Monera	Majority of Animalia and many Protista and Monera*

* Note that green plant cells do both photoautotrophy and organoheterotrophy.

$Plants_1$, $plants_2$ and life styles

- $Plants_1$ are **photoauthotrophs**
- $Plants_2$ are photoauthotrophs too but there are exceptions: **fully parasitic plants**. Formally, many parasitic plants are $plants_2$ but not $plants_1$
- Carnivorous plants (like sundew or Venus flycatcher) are all photoautotrophs! They "eat" animals to obtain fertilizers: nitrogen and phosphorous.

7 Basics of life

7.1 Chemistry of life

Very basics of chemistry

- Atoms
  - Protons
  - Neutrons
  - Electrons
- Atomic weight
- Isotopes
- Elements
- Periodic table: rows and columns
- Chemical bonds: ionic, covalent, hydrogen
- Valence and group
- Molecules
- Molecular weight

Final question (3 points)

How many protons, electrons and neutrons are in niobium atom?

Summary

- "Carnivorous" plants are not carnivores

For Further Reading

References

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

Outline

8 Questions and answers

8.1 Quiz

Quiz question (3 points)

What is the number of protons, electrons and neutrons in niobium atom?

41 protons, 41 electrons, and 52 or 51 (likely, rare) neutrons.

9 Basics of life

9.1 Chemistry of life

Very basics of chemistry

- Atoms
  - Protons
  - Neutrons
  - Electrons
- Atomic weight
- Isotopes
- Elements
- Periodic table: rows and columns
- Chemical bonds: ionic, covalent, hydrogen
- Valence and group
- Molecules
- Molecular weight

Mole: the example

To cook one molecule of water (H_2O), we need one molecule of hydrogen (H_2) and half molecule of oxygen (O_2)

To cook one **mole** of water, we need one **mole** of hydrogen and half a **mole** of oxygen

To cook 18 grams ($2 \times 1 + 16$) of water, we need 2 grams (2×1) of hydrogen and 16 grams ($\frac{16 \times 2}{2}$) of oxygen

To cook 180 grams of water, we need 20 grams of hydrogen and 160 grams of oxygen

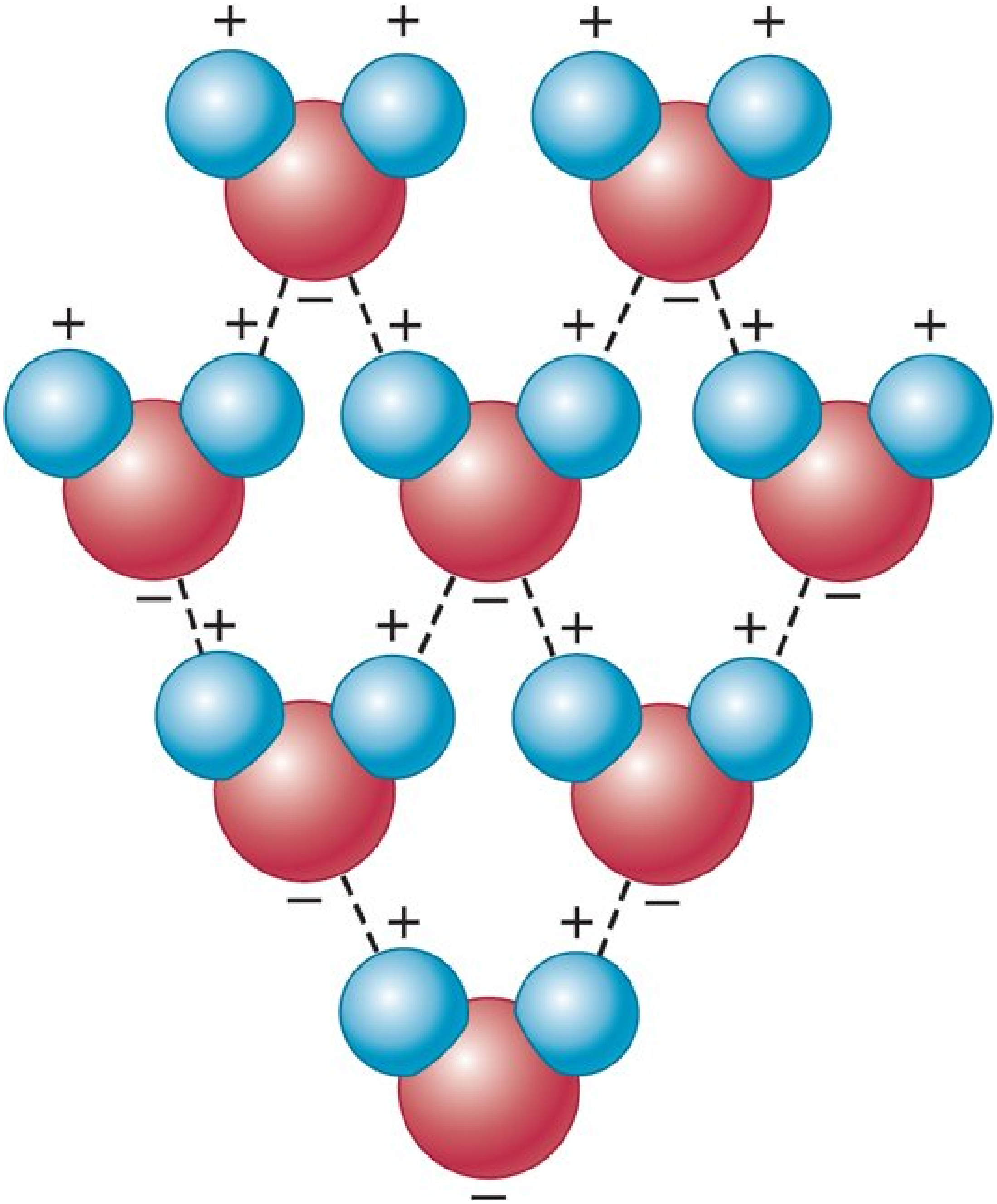
... and so on

Molar mass, mole and molar concentration

- Molar mass is a gram equivalent of molecular mass
- For example, molecular mass of salt (NaCl) is $23 + 35$[1] $= 58$ Da. We take "Da" out and replace it with "g" (grams). Therefore, 1 mole of salt is 58 g.
- Every mole contains $6.02214078 \times 10^{23}$ molecules (Avogadro's number)
- Concentration is the density of dissolved substance
- In water solution, 1 M (1 molar) concentration of salt means that in 1 liter of distilled water 58 g of salt was diluted
- If we take half of this water, colcentration will still be 1 M whereas amount of diluted salt will decrease twice

Water with hydrogen bonds

[1] If we accept that atomic mass of chlorine in 35.



Acids and bases. Ions

- Acids: take out H^+ cation (proton), like
  $HCl \to H^+ + Cl^-$
  or
  $H_2SO_4 \to 2H^+ + SO_4^{2-}$
- Bases: take out OH^- anion (hydroxyl)
  $NaOH \to Na^+ + OH^-$

Concentration of protons, and pH and acidity

- If concentration of protons is 0.1 M (1×10^{-1}, 0.1 g of protons in 1 l of water), this is an extremely acidic solution
- In distilled water, concentration of protons is equal to 1×10^{-7} (0.0000001) M
- This is because water molecules can (rarely) dissociate: $H_20 \rightarrow H^+ + OH^-$
- pH of distilled water is equal to $-\log(10^{-7}) = -(-7) = 7$
- pH of the extremely acidic solution (first example) is 1

Final question (2 points)

What is a molecular weight of hydrochloric acid, HCl?

Summary

- Most important bonds: polar and non-polar covalent (intramolecular) and hydrogen (intermolecular)

For Further Reading

References

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

Outline

10 Questions and answers

10.1 Quiz

Quiz question (2 points)

What is a molecular weight of hydrochloric acid, HCl?

$1 + 35 = 36$ atomic units (not grams!)

11 Basics of life

11.1 Molecules of life

Concentration of protons, and pH and acidity

- If concentration of protons is 0.1 M (1×10^{-1}, 0.1 g of protons in 1 l of water), this is an extremely acidic solution
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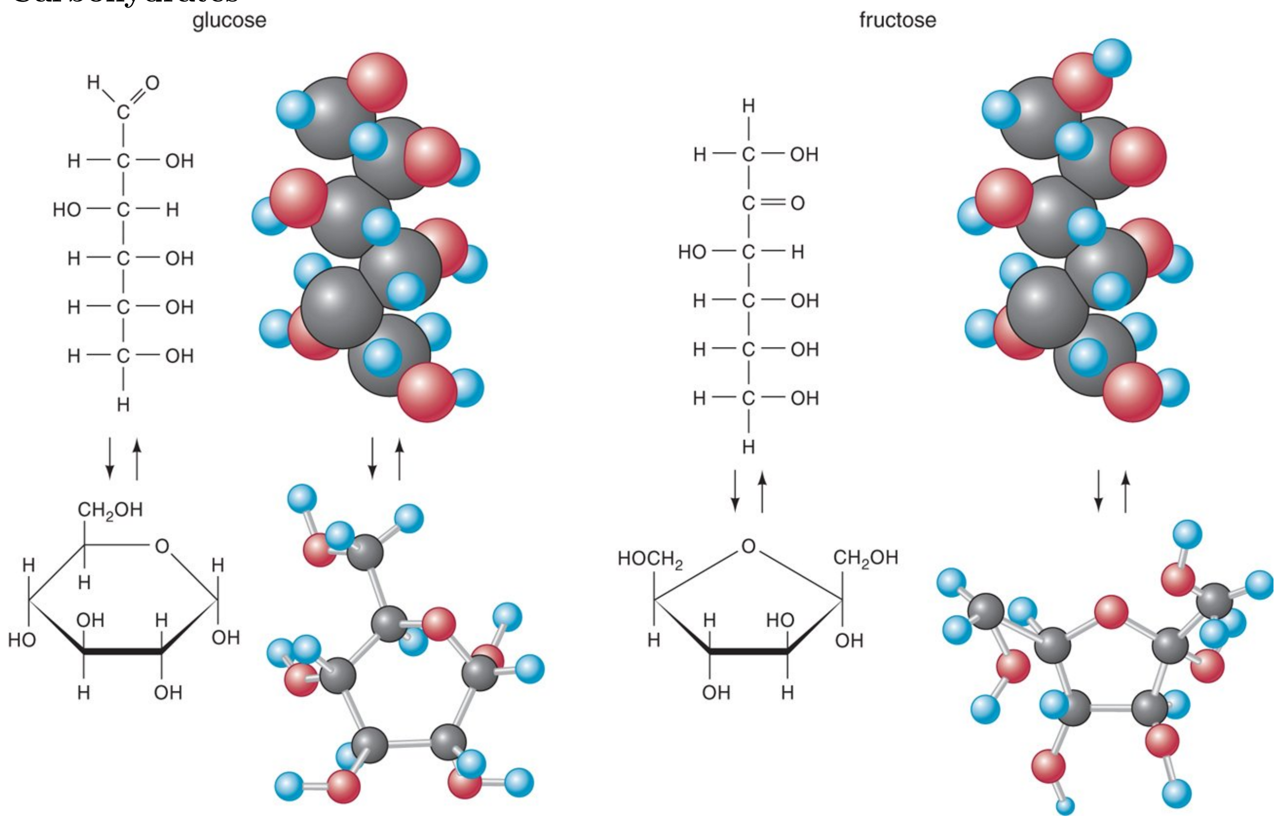
Organic chemistry: chemistry of carbon

- Carbon skeleton
- And H, O, N, P, S

Four types of biomolecules

- Lipids: hydrophobic
- Carbohydrates (sugars): multiple −OH groups
- Amino acids: N + C + O and hydrogen
- Nucleotides: cycle with nitrogen (heterocycle), sugar and phosphoric acid

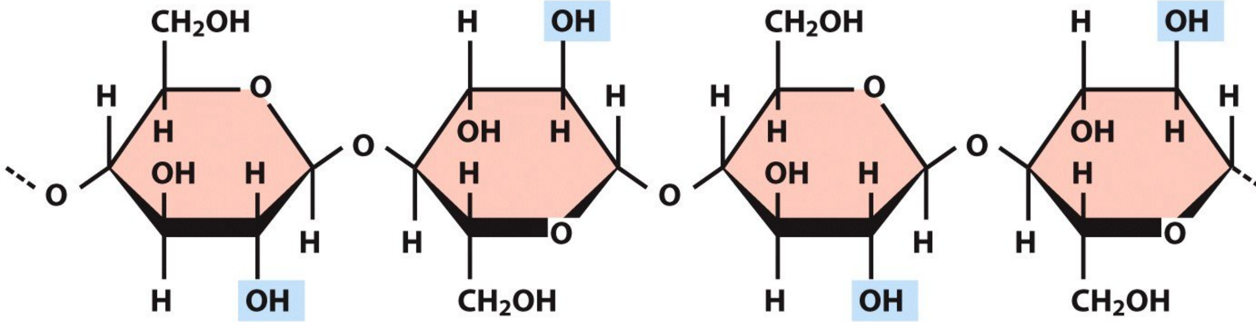
Carbohydrates



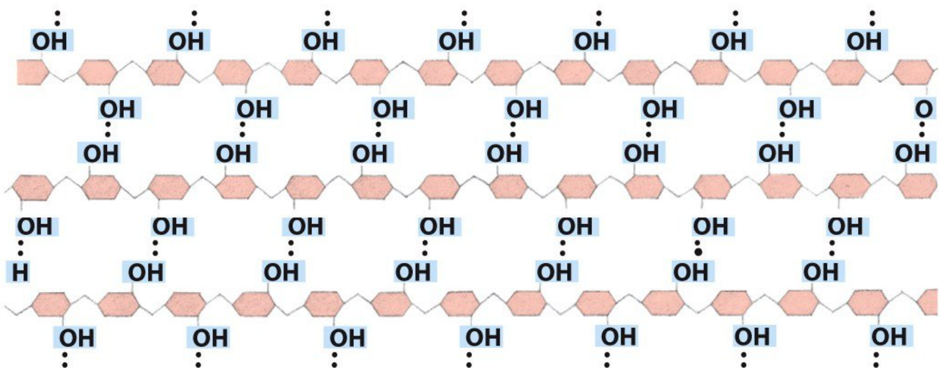
Organic polymers

- Polymeric carbohydrates: polysaccharides (like cellulose and starch)
- Polymeric amino acids: proteins
- Polymeric nucleotides: nucleic acids (DNA and RNA)

Cellulose



(a)



(b)

Summary

- Most important bonds: polar and non-polar covalent (intramolecular) and hydrogen (intermolecular)
- Obligatory biogenic elements: C, H, O, N, P
- Most important monomers: lipids, carbohydrates, amino acids, nucleotides
- Most important polymers: polysaccharides, proteins, nucleic acids

12 Photosynthesis

12.1 History of photosynthesis studies

van Helmont

- Johannes van Helmont (17th century) rejected the idea that plans take most of their biomass from soil
- Willow (*Salix* sp.) tree of 2.27 kg grew to 67.7 kg in five years, but weight of soil decreased only by 57 g
- van Helmont concluded that plants take most of their weight from water

Pristley

- Famous Joseph Pristley in 1772, made series of experiments with mouse, candle and sprig of mint (*Mentha* sp.)
- Mouse behave similar to candle, they both "spent" air
- Plant revives the air for both candle and mouse

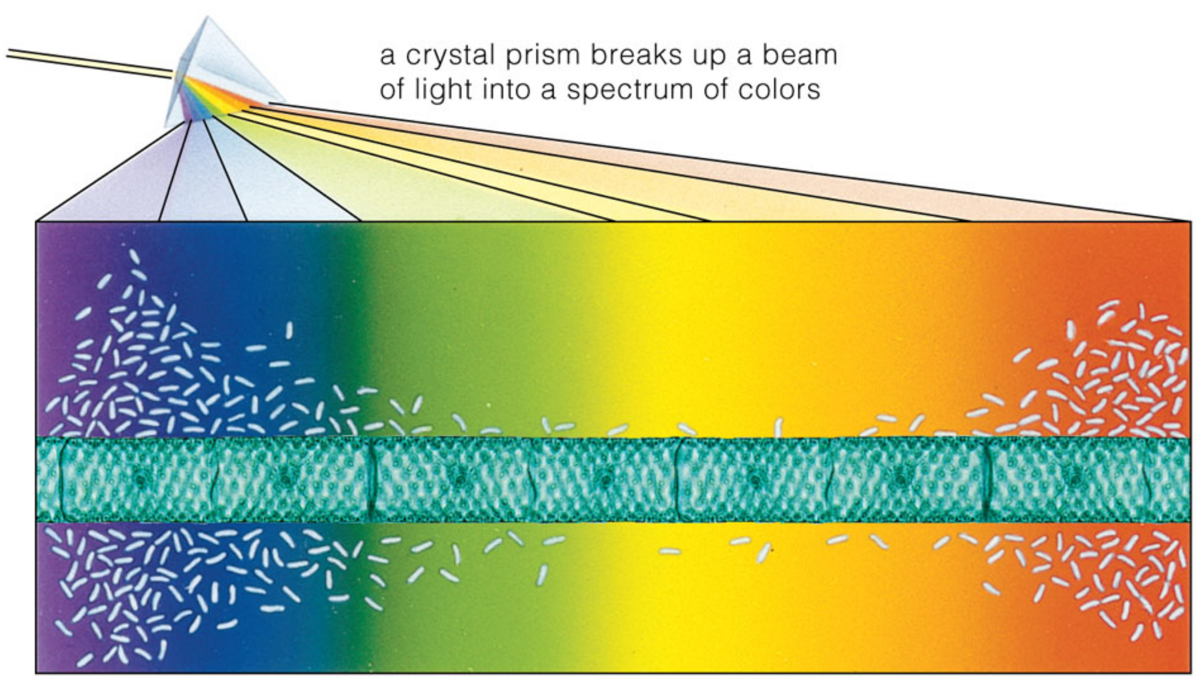
Further history

- Jan Ingenhousz (1779–1796) and Jean Senebier (1780) found that:
  - Only in day time the air is reviving
  - CO_2 is assembled
- Antoin-Laurent Lavoiser (1783) found that the "revived air" is a separate gas, **oxygen**

Engelmann

- Thomas Engelmann in 1884 found that *Spirogyra* alga produce oxygen mostly in blue and red parts of spectrum
- Therefore, the key photosynthetic pigment should accept blue and red rays and reflect green rays
- Chlorophyll fits best to this description

Experiment of Engelmann



Light and enzymatic ("dark") reactions

- Light reactions depend on the light and water, they produce oxygen and energy (in form of ATP)
- Enzymatic reactions depend on carbon dioxide and water, they take energy from light reactions and result in production of carbohydrates

Final question (2 points)

Why did Engelmann decide that photosynthetic pigment has a green color?

Summary

- Main biogenic elements: C, H, O, N, P
- Most important monomers: lipids, carbohydrates, amino acids, nucleotides
- Most important polymers: polysaccarides, proteins, nucleic acids
- From 17th century, in constantly become clear that plants make their biomass from light, water and carbon dioxide

For Further Reading

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Outline

13 Questions and answers

13.1 Quiz

Quiz question (2 points)

Why did Engelmann decide that photosynthetic pigment has a green color?

...

- Because he saw that *oxygen-loving bacteria are concentrating only in places where red and blue light present.* It means that pigment of question accepts blue and red so it is green.
- In other words:

  There are many pigments in plants. Which of them is responsible for photosynthesis?

  Photosynthesis makes oxygen AND bacteria like oxygen AND bacteria concentrate around blue and red spots → photosynthesis is going on these blue and red spots → photosynthetic pigment accepts blue and red (but not green) → photosynthetic pigment IS green.

14 Photosynthesis

14.1 History

Blackman

- In 1905, Frederick Blackman discovered that if light intensity is low, increase of temperature has a little effect on the rate of photosynthesis. But if temperature is low, light works!

  A. If light and temperature were completely *independent*, this could not happen

  B. If temperature and light were *components of the chain*, then light was first and temperature second

- Consequently, photosynthesis has two stages:

  A. Light stage which relates more with light intensity

  B. "Dark" (now called *enzymatic*) stage which relates more with temperature

Light and enzymatic ("dark") reactions

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Four equations of photosynthesis

A. $6CO_2 + 6H_2O \xrightarrow{\text{light}} C_6H_{12}O_6 + 6O_2$ is *not a formula*, but merely a general description of a process

B. Water molecules arise from both sides, and the better formula is $6CO_2 + 12H_2O \xrightarrow{\text{light}} C_6H_{12}O_6 + 6H_2O + 6O_2$

   or even

C. carbon dioxide + hydrogen donor $\xrightarrow{\text{light}}$ carbohydrate + water + oxidized hydrogen donor

D. And the best one is probably $CO_2 + H_2O \xrightarrow{\text{light}}$ carbohydrates $+ H_2O + O_2$

14.2 Light stage: electron transport, synthesis of ATP and NADPH

Participants of light stage

A. Chlorophyll (photosystems II and I)

B. Light

C. Water

D. ATP synthase (ATPase)

E. Protons (H^+)

F. Hydrogen carrier ($NADP^+$)

Where: around thylakoid membrane

Logic of the light stage

A. To assemble carbon dioxide into sugar, we need ATP

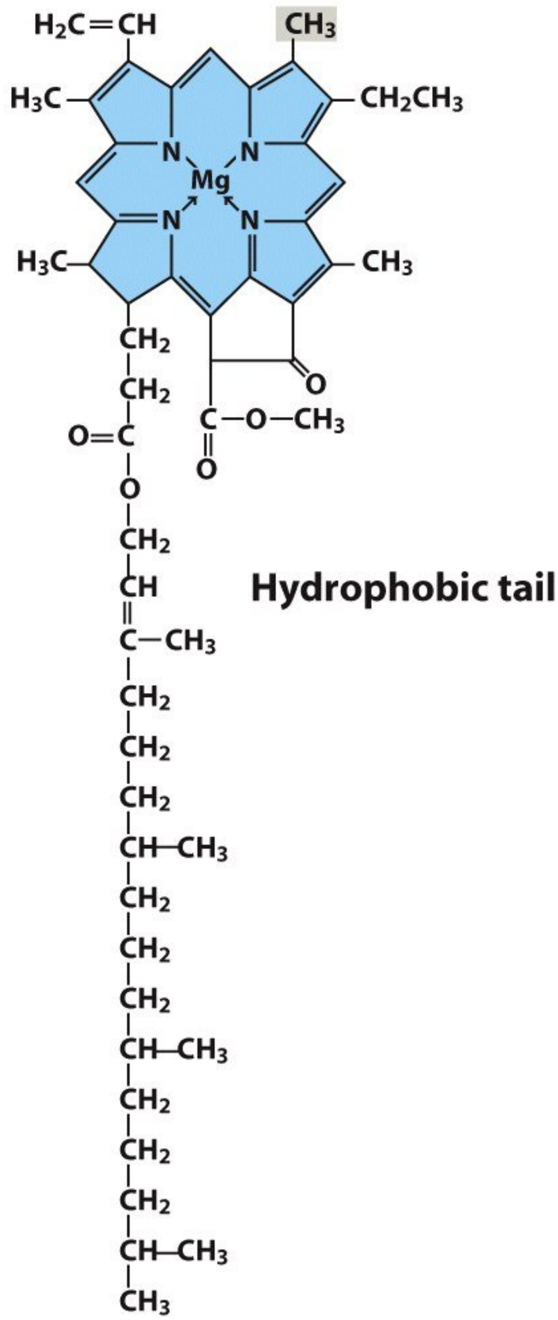
B. To make ATP, we need *electrical current* through the proton pump

C. To make this current, we need the *difference in charge* (voltage difference) between thylakoid and matrix (stroma) compartments

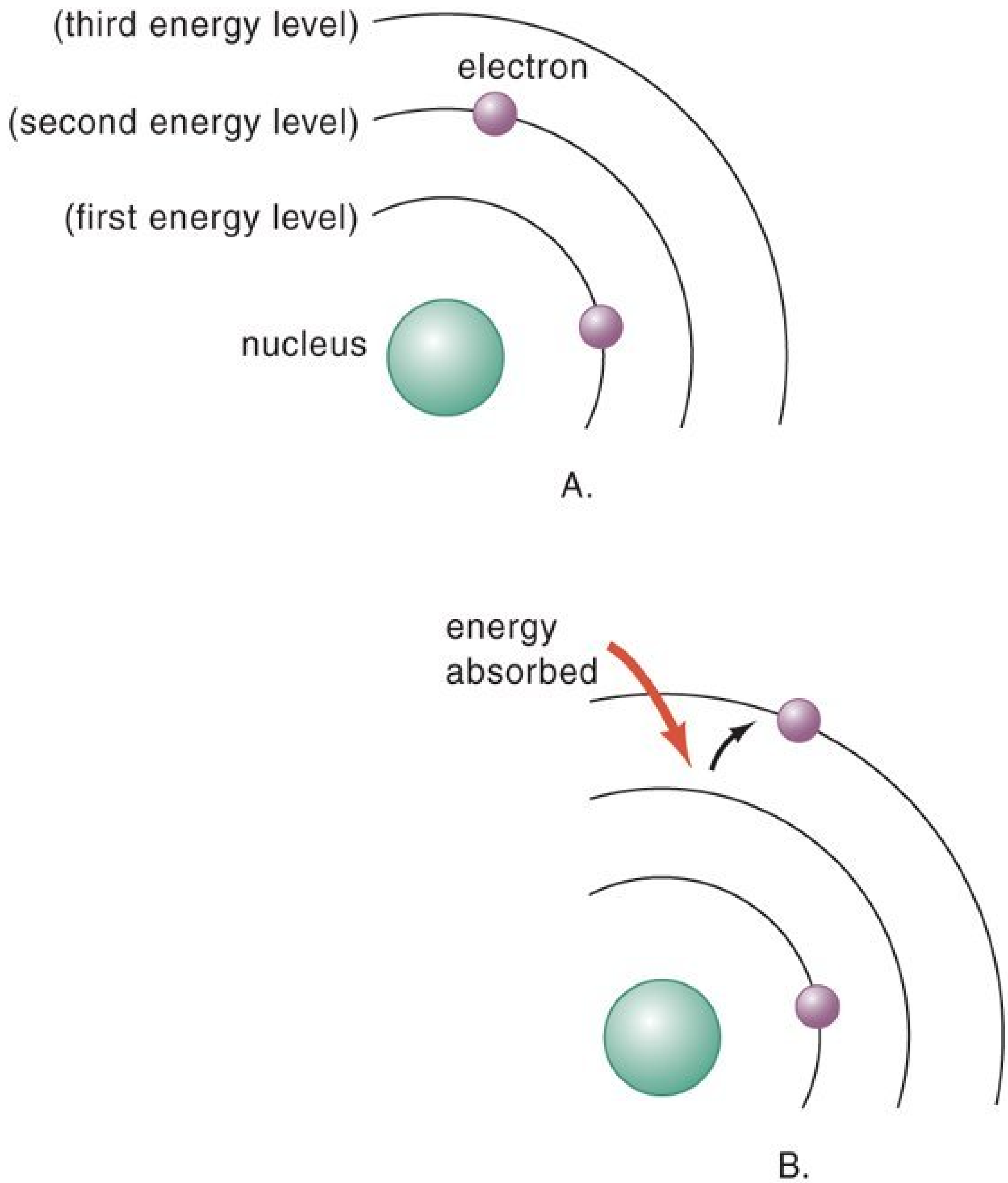
D. To make this difference, we need to *segregate ions*: positively charged (like H^+) will go from outside and stay inside, negatively charged (like e^- and OH^-) will go from inside and stay outside

E. To segregate ions, we need the energy and the energy booster. These are sun rays and chlorophyll

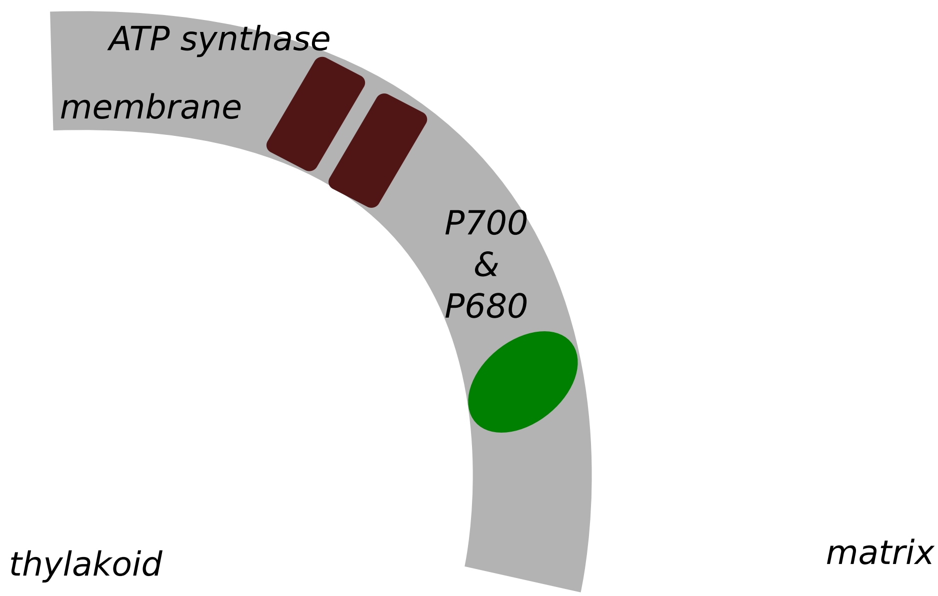
Why chlorophyll is good for the membrane

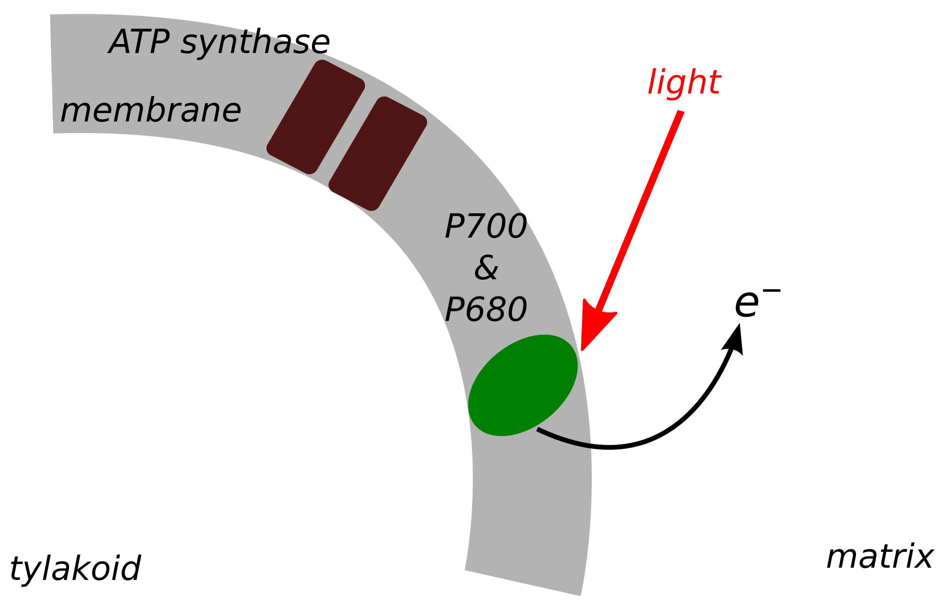


How chlorophyll works: excitation of the electron



Scheme of light stage





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

For Further Reading

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Outline

15 Photosynthesis

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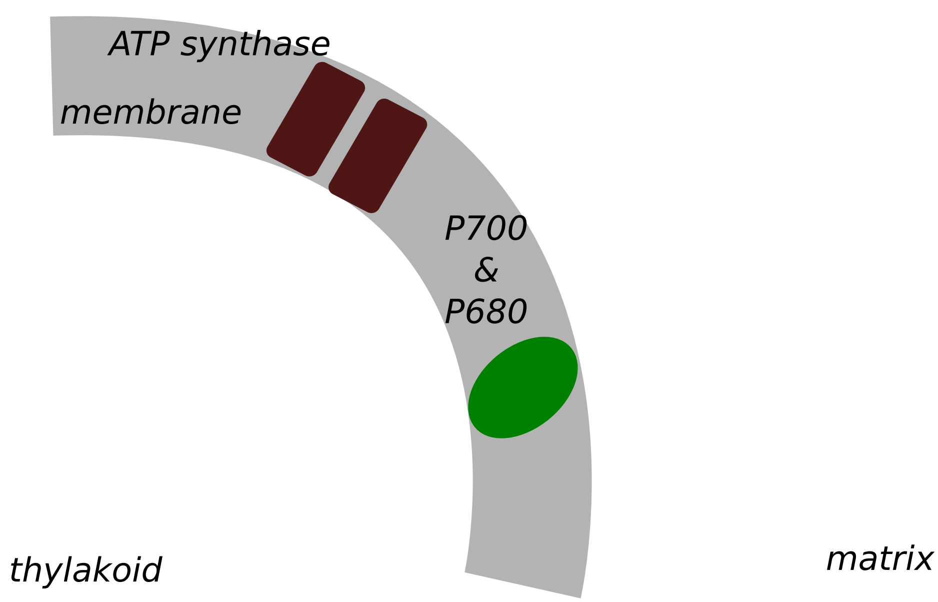
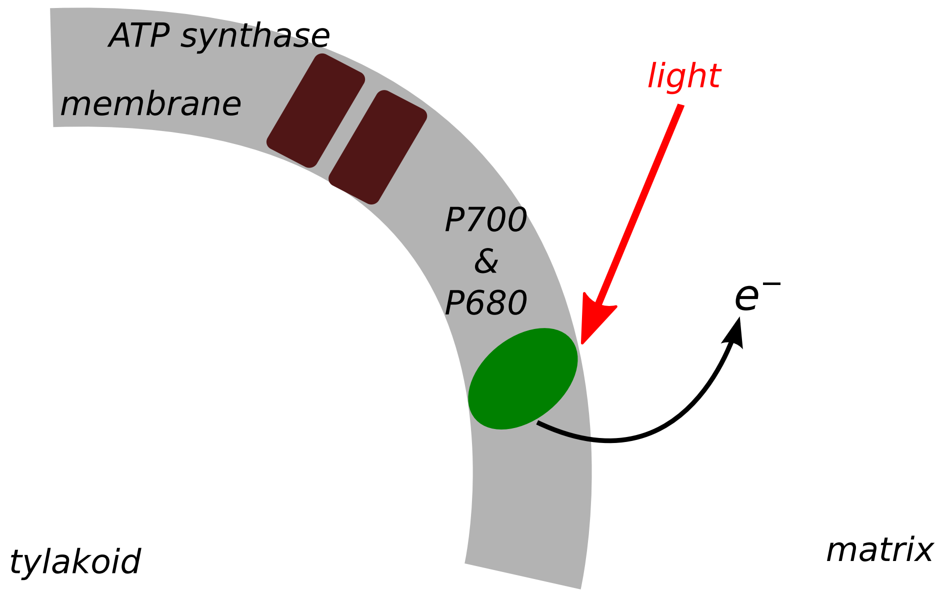
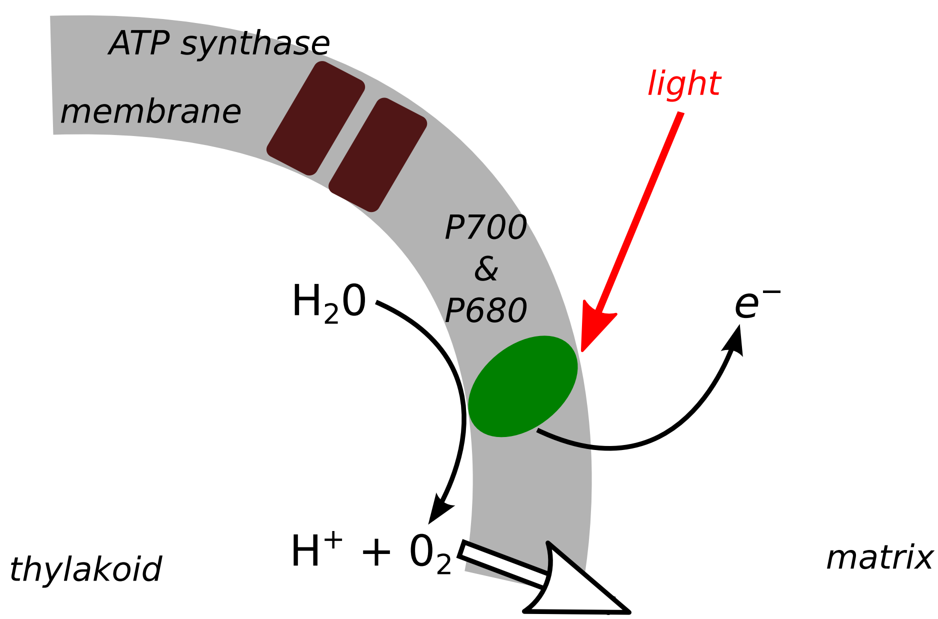



ATP synthase
membrane
light
P700
&
P680
e^-
tylakoid
matrix


ATP synthase
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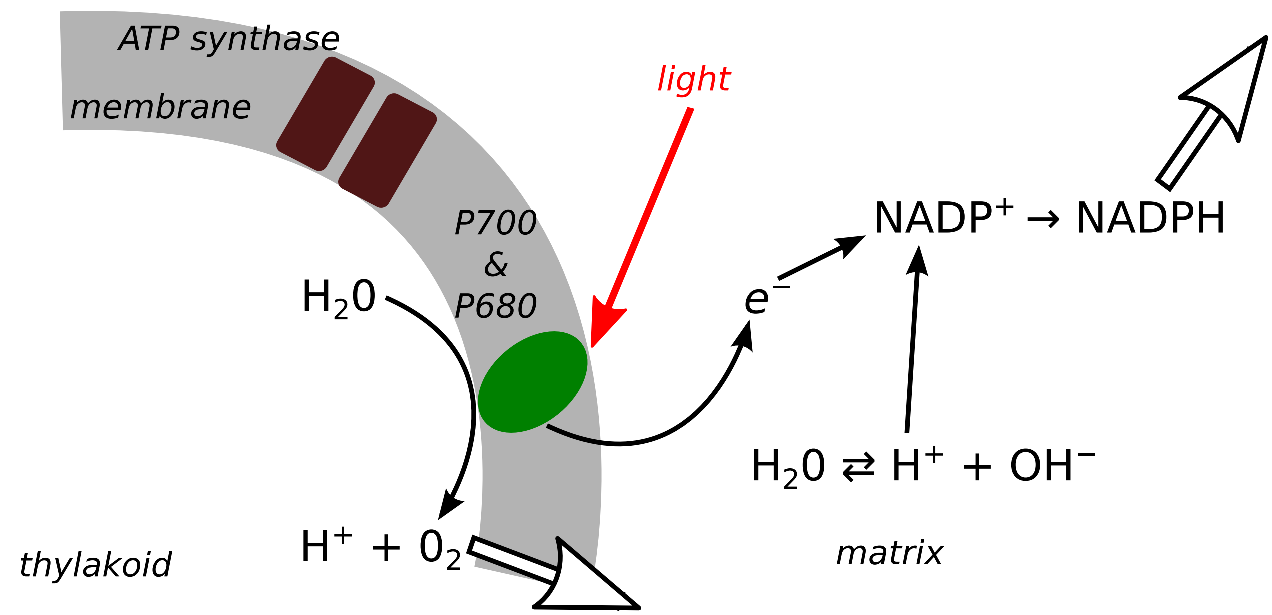
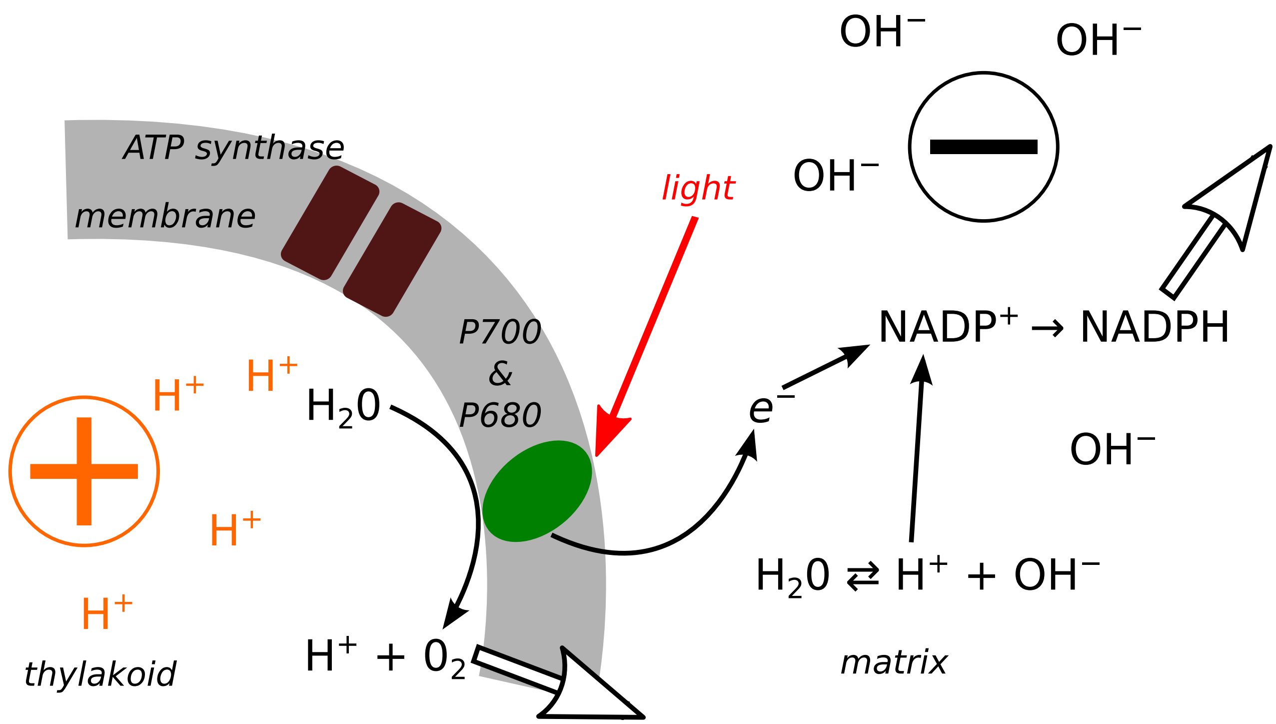
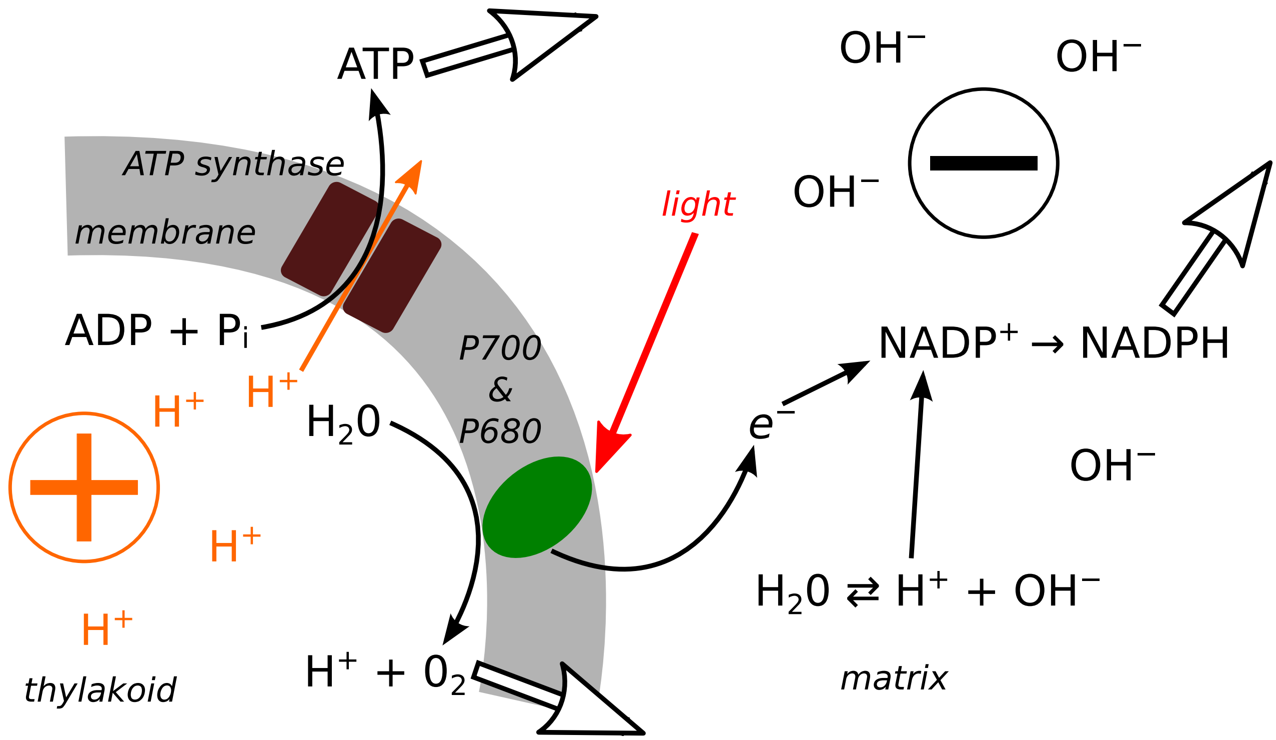
H_20
e^-
$H^+ + 0_2$
thylakoid
matrix


ATP synthase
membrane
light
P700
&
P680
H_2O
e^-
$NADP^+ \rightarrow NADPH$
$H_2O \rightleftarrows H^+ + OH^-$
$H^+ + O_2$
thylakoid
matrix


OH^-
OH^-
ATP synthase
membrane
OH^-
light
P700
&
P680
$NADP^+ \rightarrow NADPH$
H^+
H^+
H_2O
e^-
OH^-
H^+
$H_2O \rightleftarrows H^+ + OH^-$
H^+
thylakoid
$H^+ + O_2$
matrix



Main events of light stage

A. Chlorophyll + Light $\longrightarrow$ Electron (e^-) + Chlorophyll$^+$

B. e^- + H^+ (from water) + Hydrogen carrier ($NADP^+$) $\longrightarrow$ NADPH (moves away)

C. $H_2O \longrightarrow H^+$ (accumulates inside) + e^- + O_2

D. H^+ (inside) + OH^- (from water, located outside) $\Longrightarrow$ gradient $\Longrightarrow$proton pump $\Longrightarrow$ H_2O TOGETHER WITH ADP + P_i (inorganic phosphate) $\longrightarrow$ **ATP**

Photosystems

- Photosystem II (P_{680}, contains chlorophylls and carotene):

  A. decomposes water;

  B. forwards electron to Photosystem I;

  C. makes proton gradient

- Photosystem I (P_{700}, contains only chlorophylls) makes NADPH

Photosystems movie

Results of the light stage

At the start	At the end
H_2O	H_2O (result of pump) and $\mathbf{O_2}$
Chlorophylls	Chlorophylls
ADP and P_i (inorganic phosphate)	ATP
$NADP^+$	NADPH

Quiz question (2 points)

Explain the role of $NADP^+$

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

For Further Reading

References

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

Outline

16 Questions and answers

16.1 Quiz

Final question (2 point)

Explain the role of hydrogen carrier ($NADP^+$)

- In the light stage of photosynthesis, with the help of Photosystem I (P_{700}) it takes hydrogen (protons from water and electrons from chlorophyll) and removes them from the space outside of membrane
- Hydrogen used in enzymatic reactions
- Accumulated OH^- helps with the gradient and therefore with the electrical current through ATPase

17 Photosynthesis

17.1 Enzymatic stage: fixation of carbon dioxide

Participants of enzymatic stage

A. Carbon dioxide (CO_2)

B. Hydrogen carrier with hydrogen (NADPH)

C. Source of energy (ATP)

D. Ribulose biphosphate (RuBP, five-C-hydrocarbonate, "C_5")

E. *Rubisco* and other enzymes

Place: in the matrix (stroma) of chloroplast

Main events of enzymatic stage

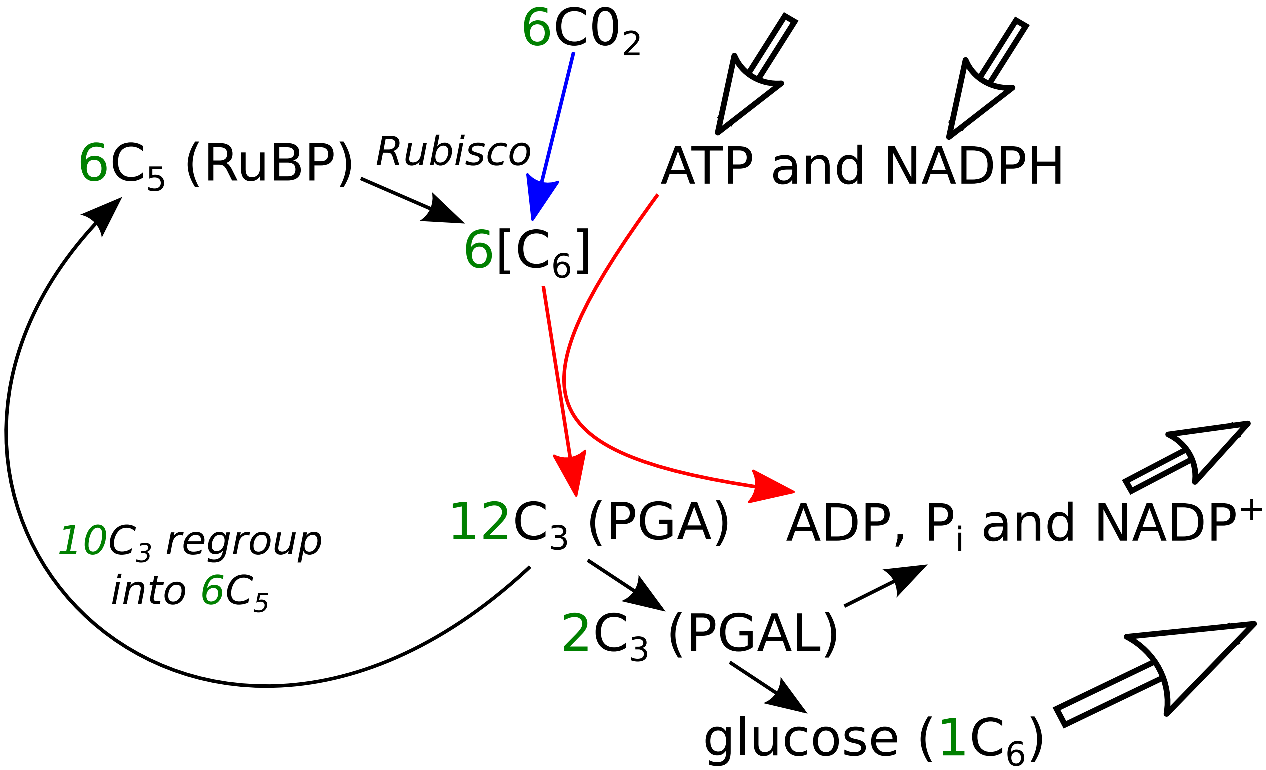
A. $CO_2 + C_5$ (RuBP, ribulose biphosphate) $\xrightarrow{\text{Rubisco}} C_6$

B. $C_6 \longrightarrow 2C_3$ (PGA, phosphoglyceric acid)

C. C_3 + NADPH + ATP $\longrightarrow C_6H_{12}O_6$ (or other organic molecules) + C_5 + $NADP^+$ + ADP + P_i (inorganic phosphate)

- Organic molecules are synthesized from C_3 (PGA) through energy-rich **PGAL** (phosphoglyceric aldehyde)

Enzymatic stage: scheme



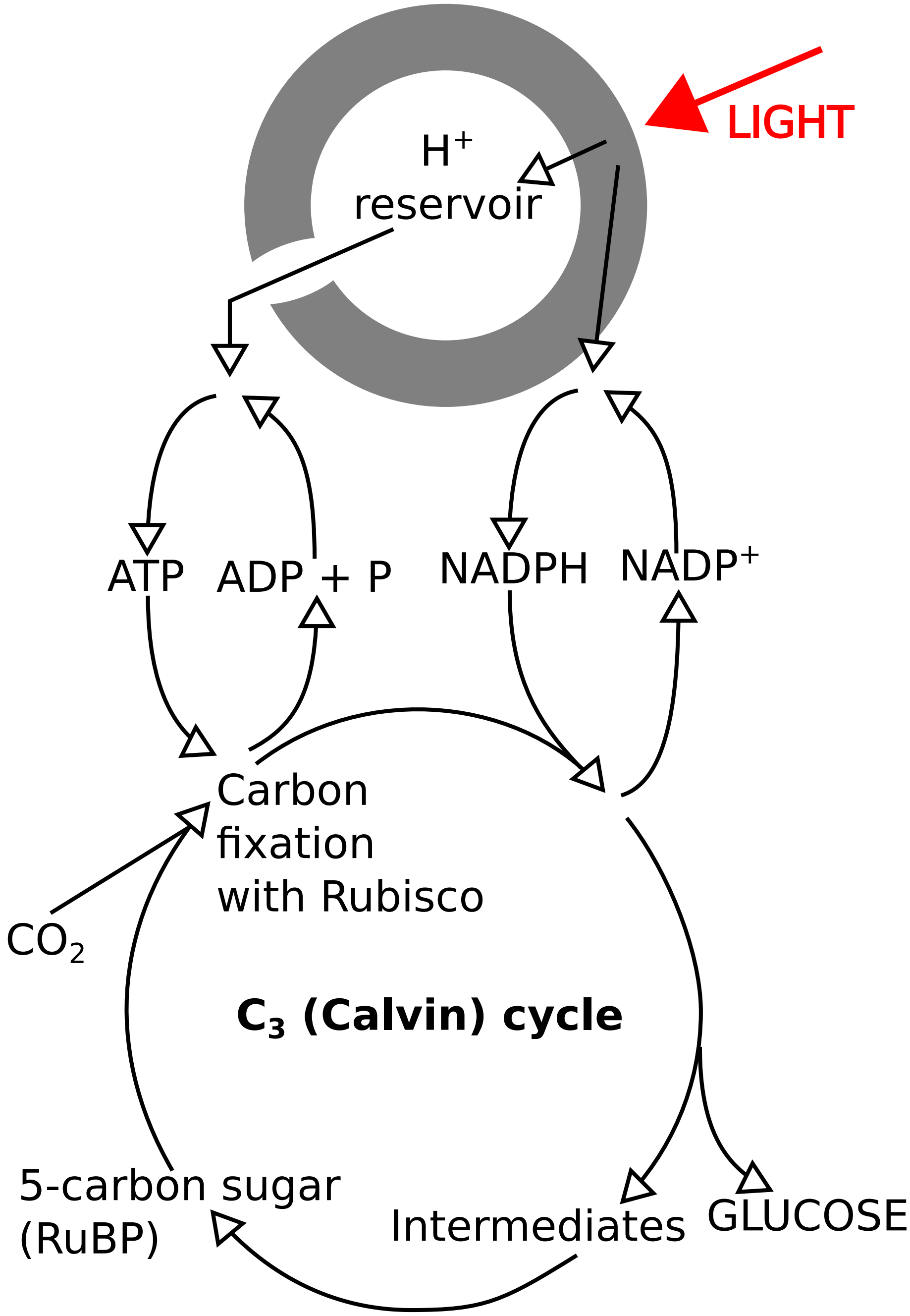
Results of enzymatic stage

At the start	At the end
CO_2	$C_6H_{12}O_6$ (or other organic molecules)
NADPH	$NADP^+$ (H goes to $C_6H_{12}O_6$)
ATP	ADP and P_i (inorganic phosphate)
C_5	C_5
Rubisco	Rubisco

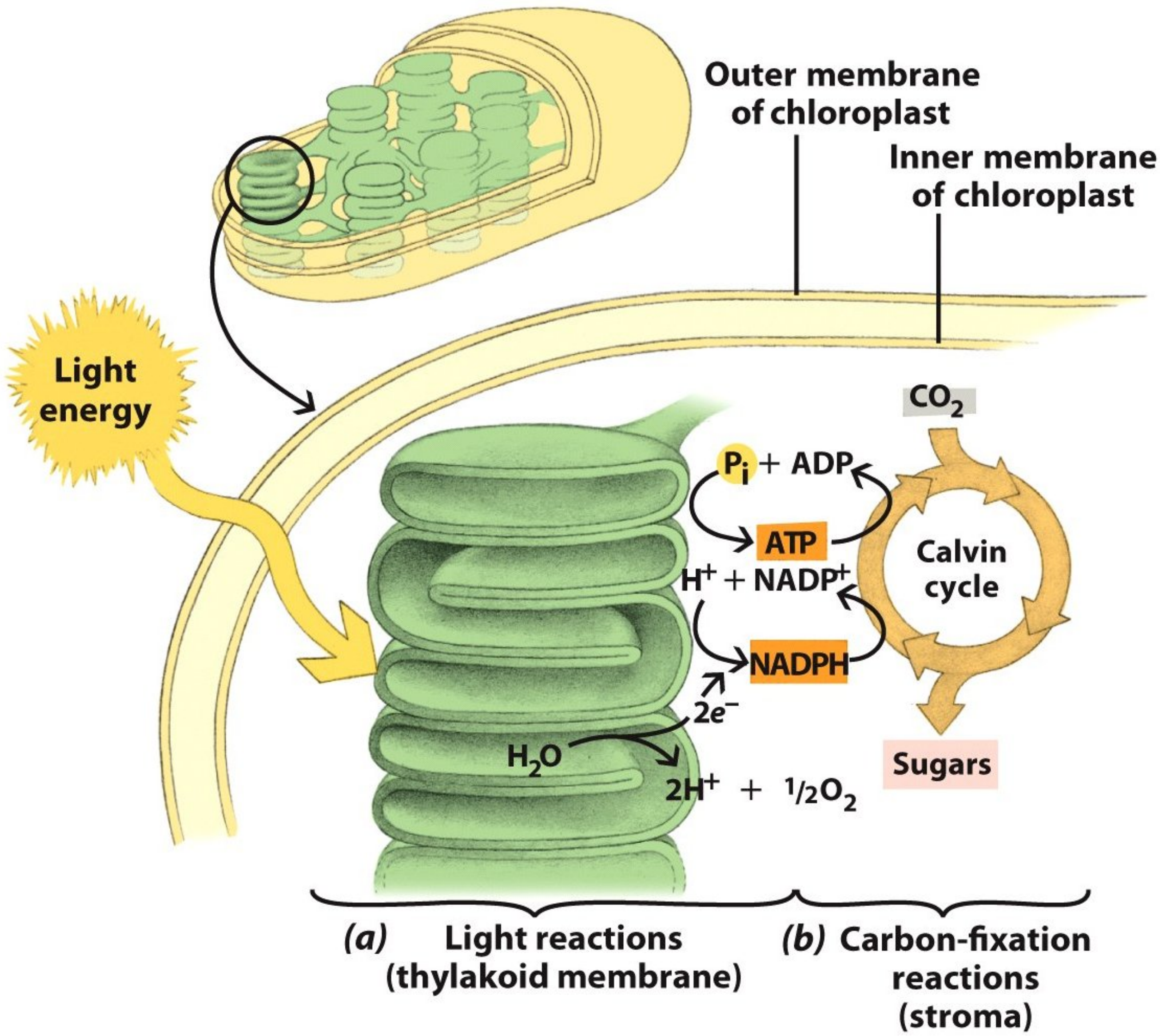
The other names for enzymatic stage are “Calvin cycle” and “C_3 cycle”

17.2 As a whole

Overview of photosynthesis



Photosynthesis in the cell



Photosynthesis movie

Final question (2 points)

Explain the role of NADPH in the enzymatic stage.

Summary

- **Photosynthesis** is a sum of light-dependent (photo-) and light-independent (auto-) reactions
- **Light stage** of photosynthesis results in accumulation of energy and hydrogen, and release of oxygen
- **Enzymatic stage** of photosynthesis results in assimilation of the CO_2 and synthesis of organic molecules

For Further Reading

References

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

Example questions for the exam

Start time __________________ *End time* __________________

Short answers

A. Why do carnivorous plants catch insects? Explain. (*4 points*)

Multiple choice

Every question in this section costs either 2 or 0. Please **mark** the appropriate answer on the **scantron**.

A. Which set of three components can make a amino acid?

   (a) Oxygen, hydrogen, nitrogen and carbon skeleton

   (b) Phosphoric acid, sugar and carbon cycle with nitrogen

   (c) Lipids and nitrogen

B. In photosynthesis, water used to make:

   (a) Carbon dioxide

   (b) Oxygen

   (c) More water

C. Dodder is:

   (a) Plant_1 (ecological definition) and plant_2 (taxonomic definition)

   (b) Plant_1 only

   (c) Plant_2 only

(answers on next page)

Answers: 1A, 2B, 3C

Outline

18 Questions and answers

18.1 Quiz

Final question (2 points)

...

- ...

19 Photosynthesis

19.1 Special case of photosynthesis: C_4 pathway

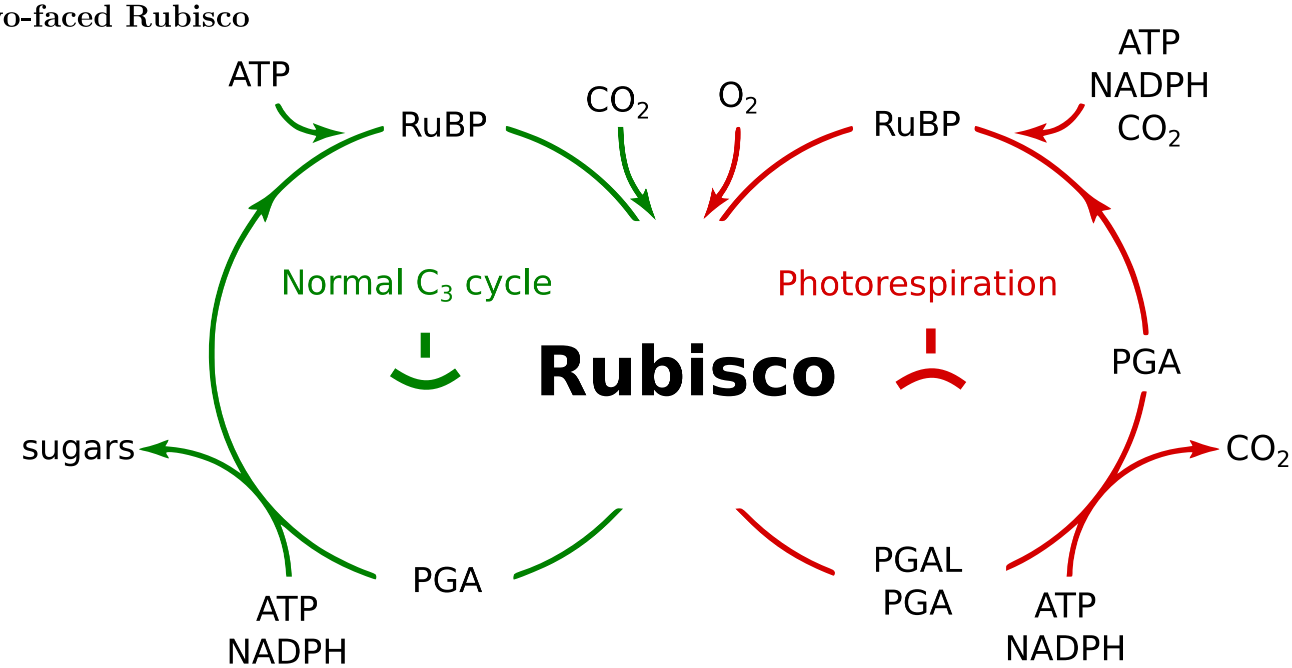
Photorespiration

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

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

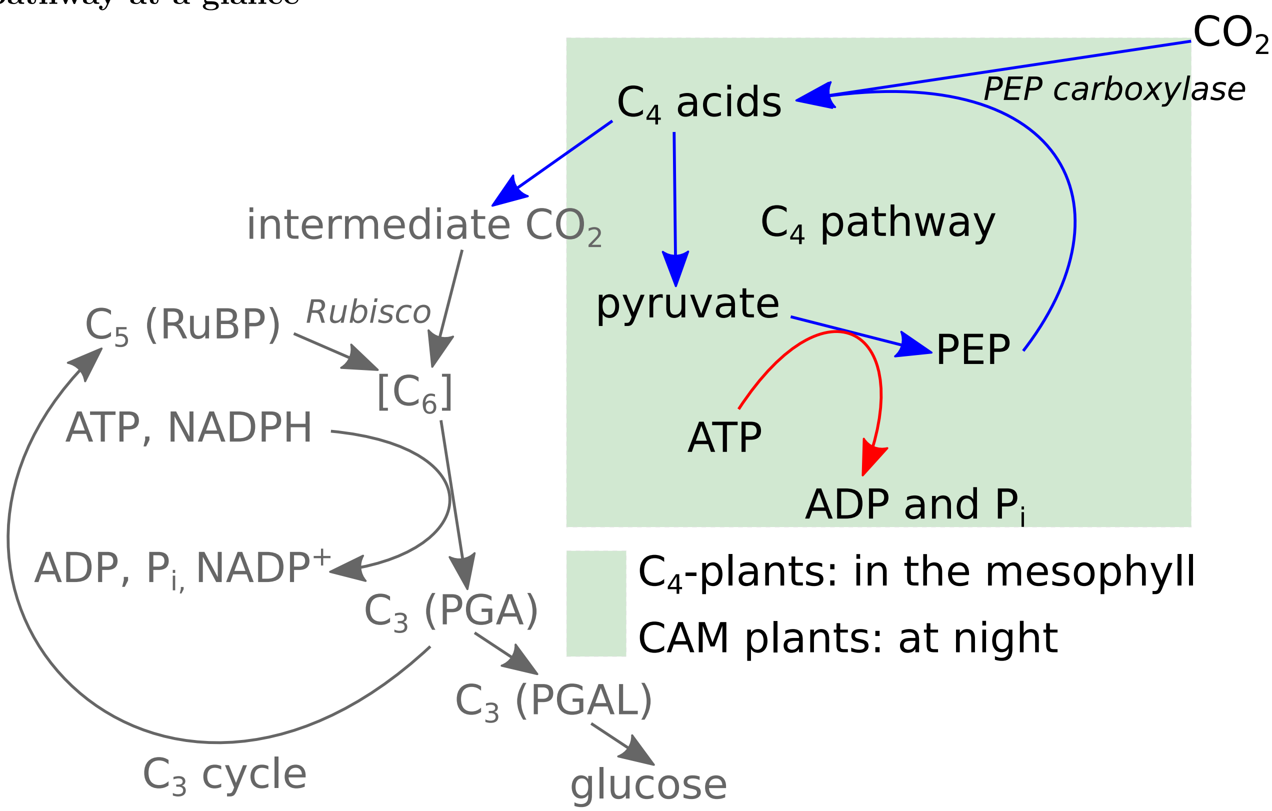
A. $CO_2 + C_5$ (PEP, phosphoenolpyruvate) $\xrightarrow{\text{PEP carboxylase}}$ C_4 (different organic acids): this is the temporarily accumulation of carbon dioxide

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

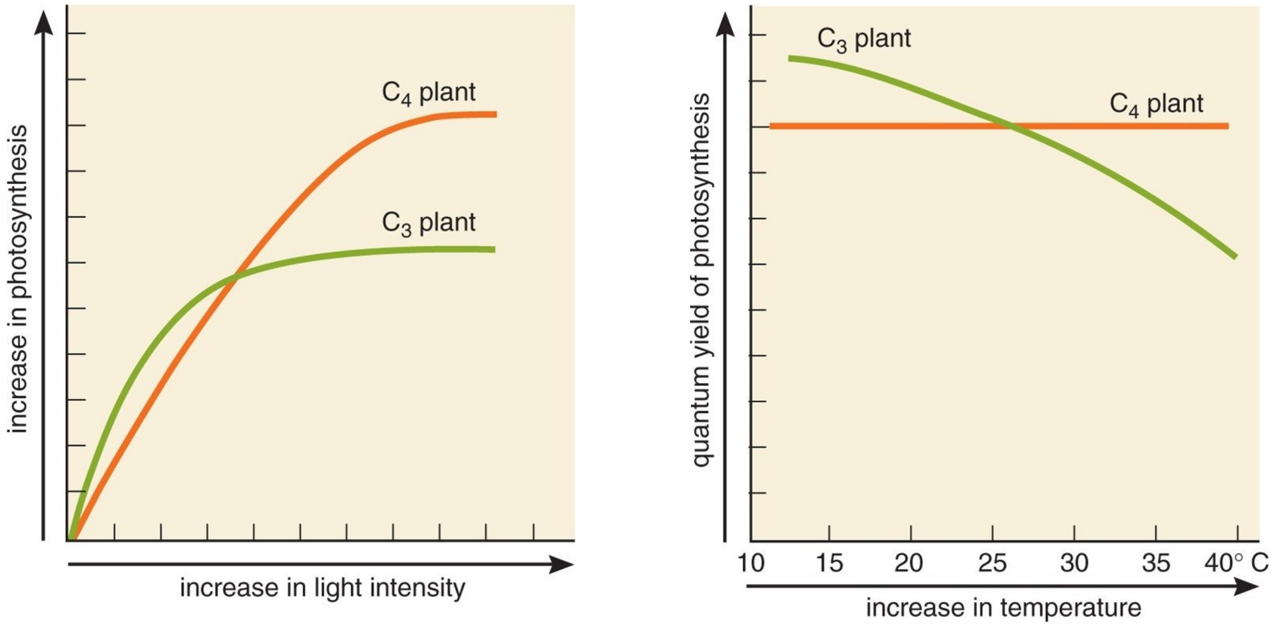
C. Pyruvate + ATP $\longrightarrow$ PEP + ADP + P_i: PEP recovery costs ATP! (but **less** then photorespiration)

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

19.2 C_4 and CAM plants

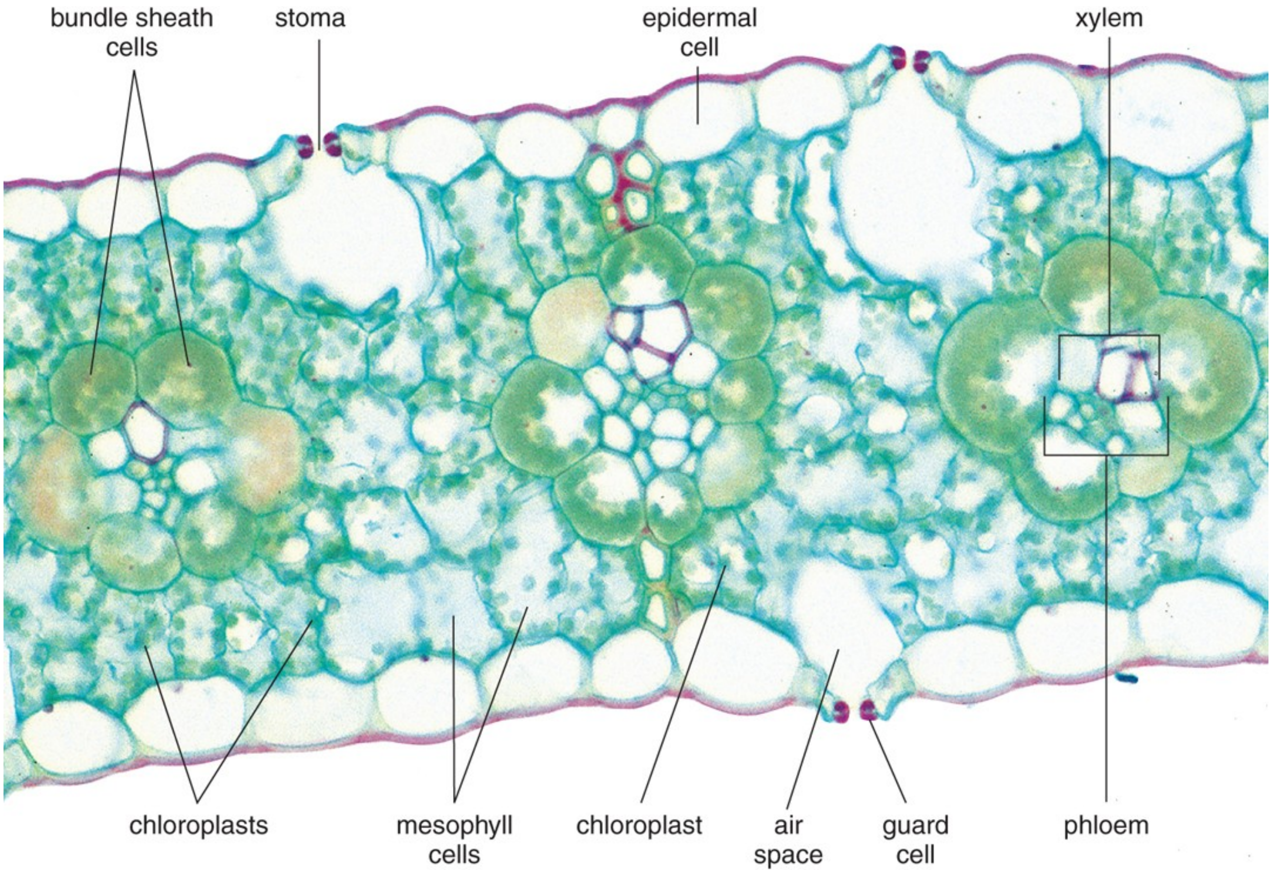
C_4 and CAM plants both use C_4 pathway

- **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.

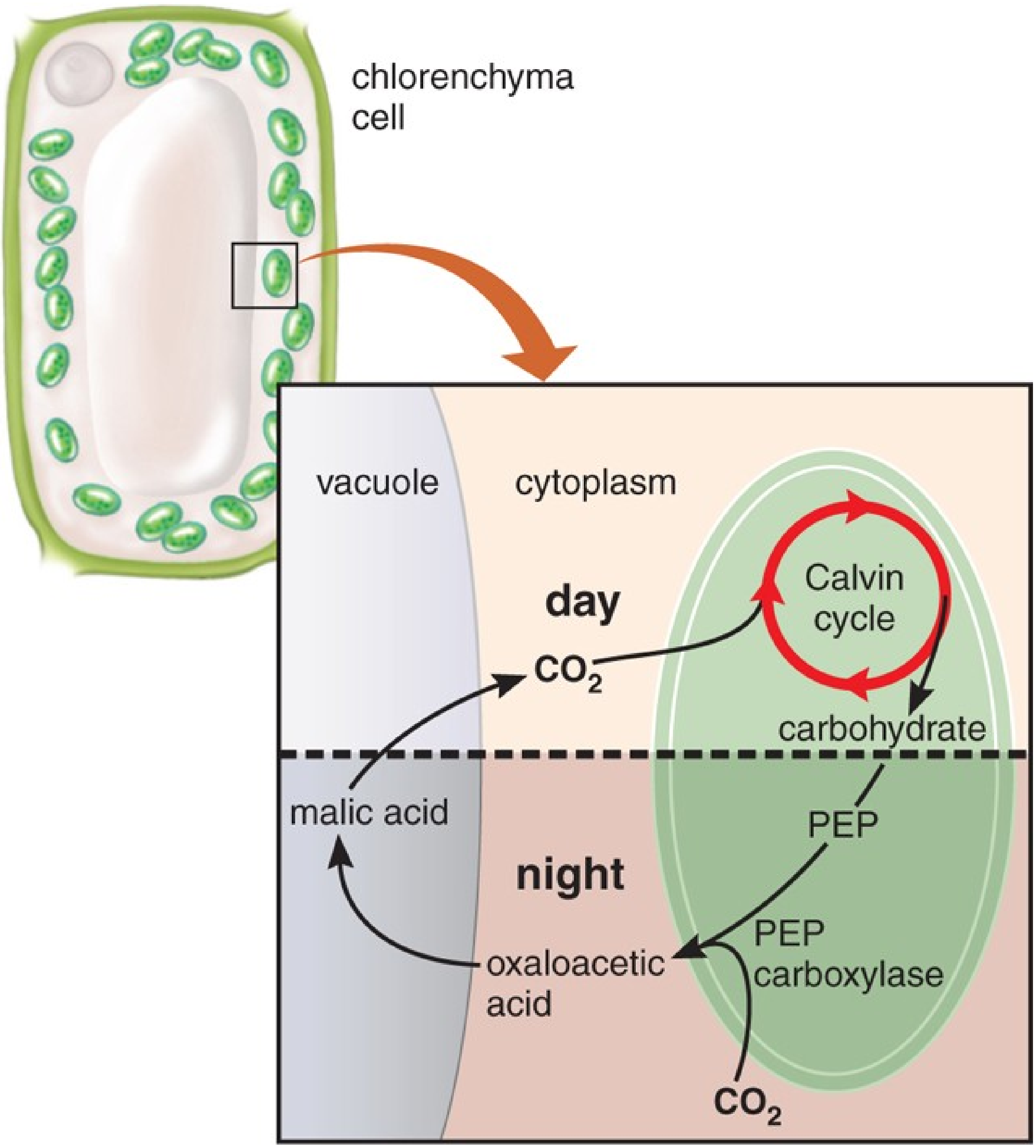
- **C_4-plants** which drive C_4 in mesophyll cells and C_3 in bundle sheath cells:
  - This is a **spatial** separation between accumulation of CO_2 and photosynthesis: C_4 pathway is located in "normal" mesophyll cells whereas the Calvin cycle is separated to **bundle sheath cells**.
  - C_4-plants (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*).

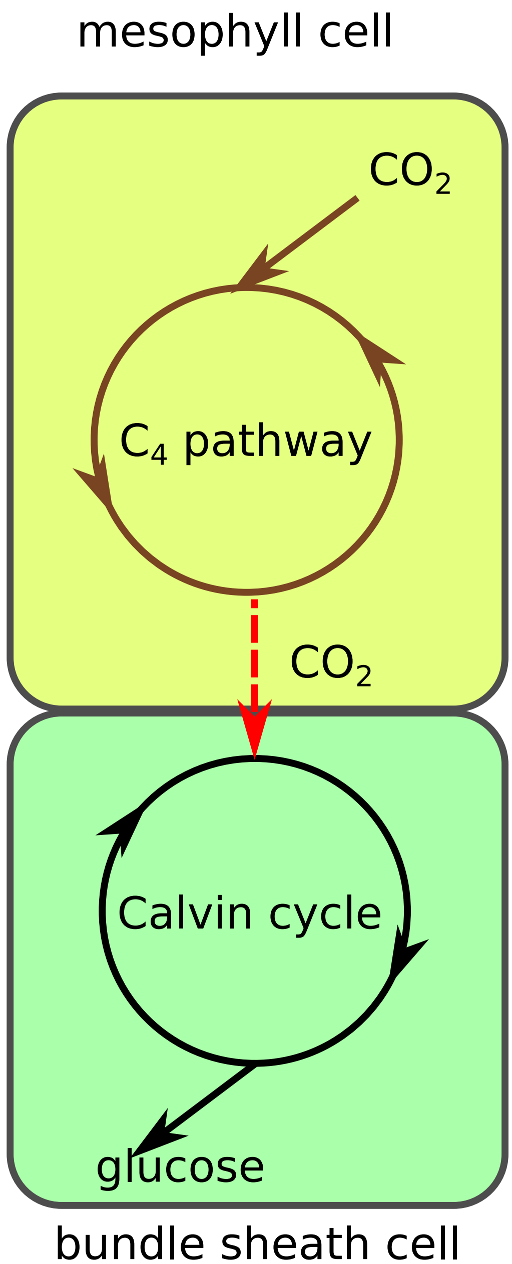
Leaf of C_4 plant: spatial separation of C_3 and C_4 pathways

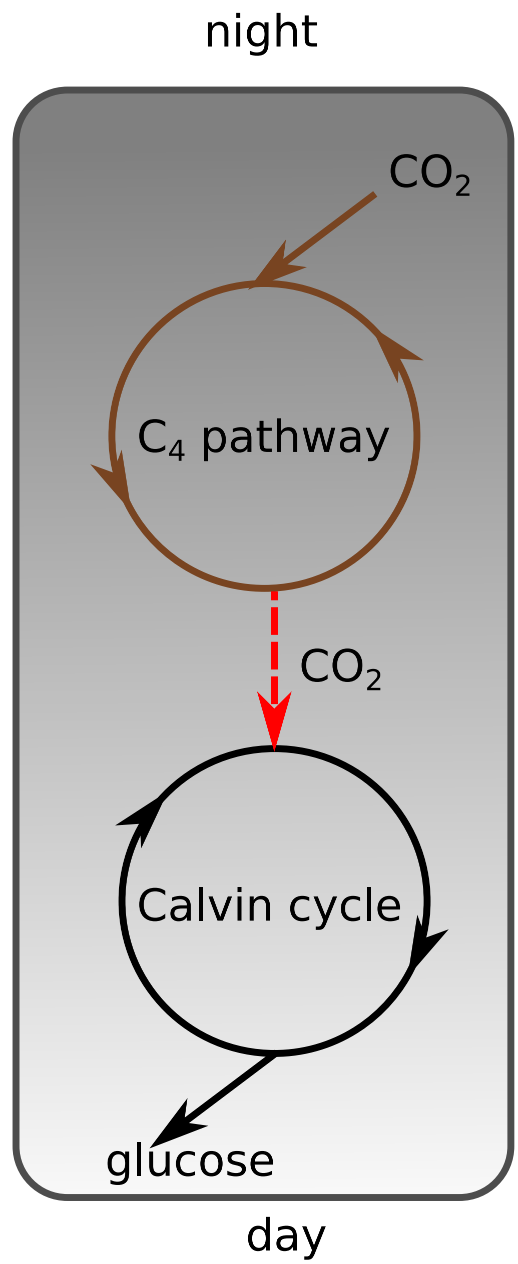


CAM plants separate C_3 and C_4 pathways in time



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

20 Questions and answers

20.1 Quiz

Results of the first exam

Results of the first exam

Lab attendance

Lab attendance

Final question (2 points)

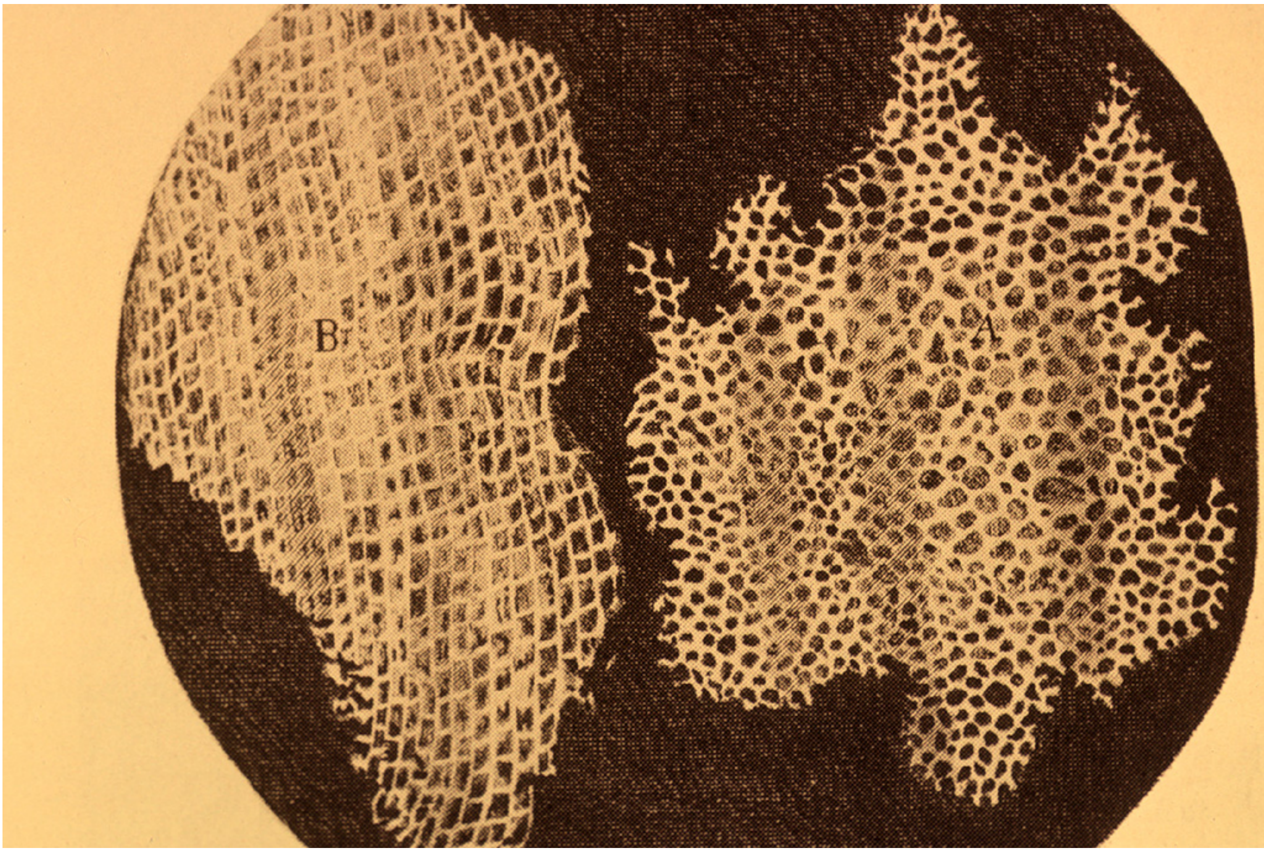
Why do plants need a C_4 pathway?

- They need it to suppress photorespiration

21 Plant cell

21.1 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

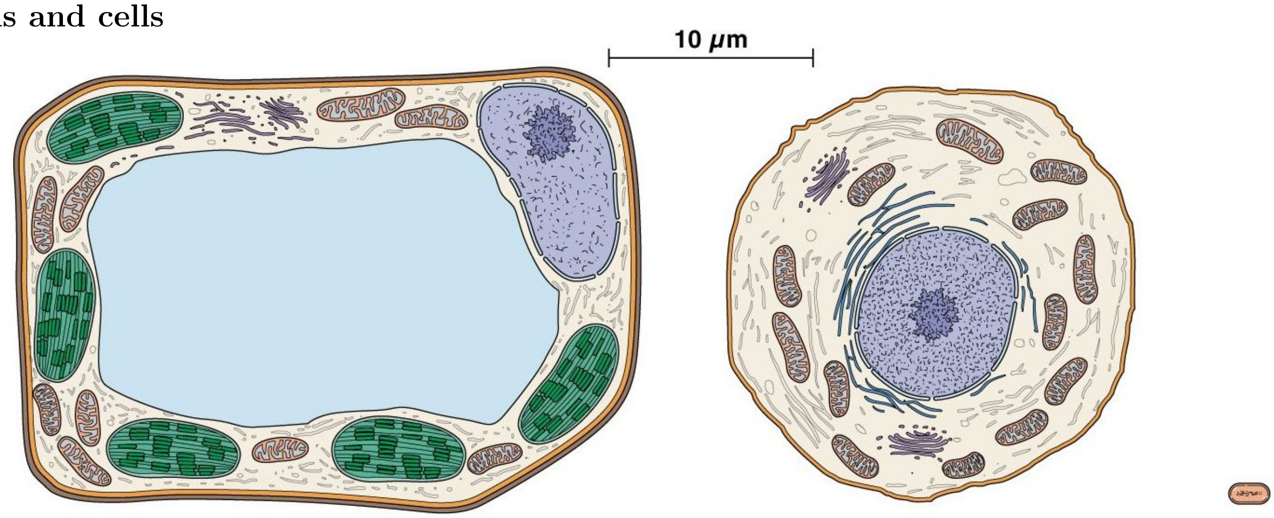
Light microscopy was an early technological breakthrough that contributed to our understanding of cell structure. Dissectiscopes use reflected light, microscopes use translucent light. Magnification is of 10^3 order.

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.

21.2 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

22 Questions and answers

22.1 Quiz

Quiz question (2 points)

...

- ...

23 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**

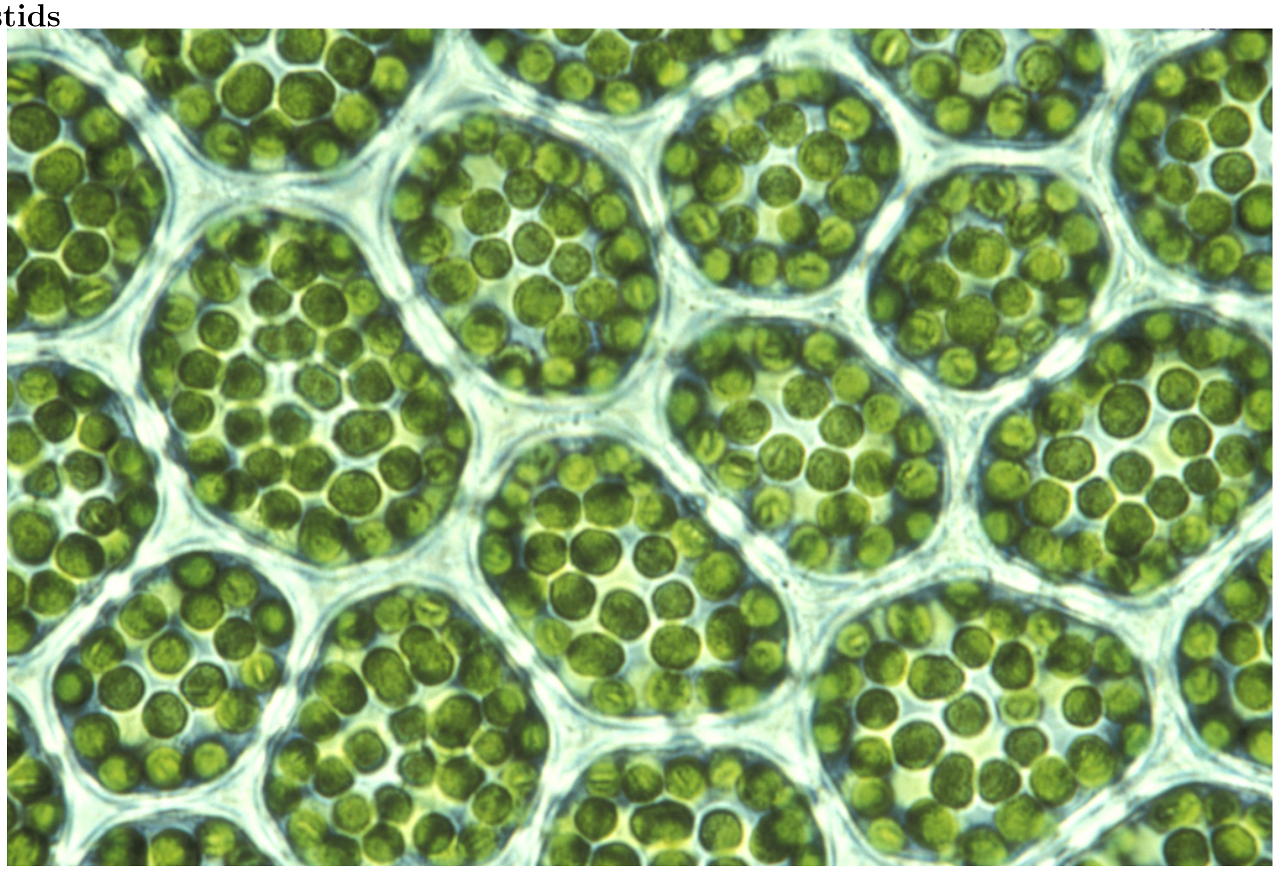
Chloroplasts and mitochondria are both results of symbiogenesis

23.1 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

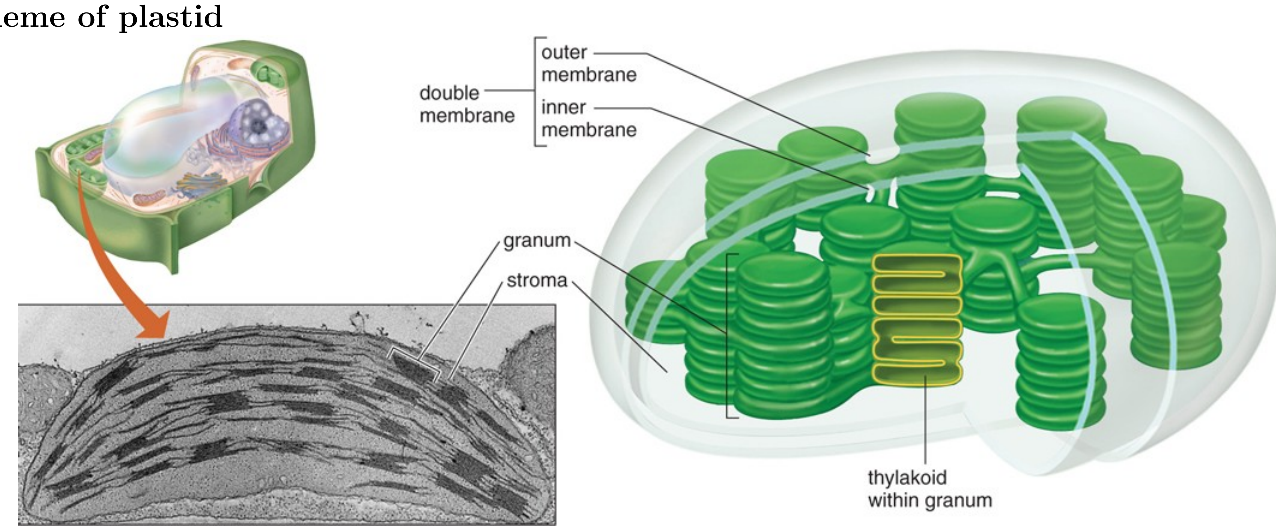


Green plastids (chloroplasts) in leaf cells of *Rhizomnium pseudopunctatum* (LM ×500)

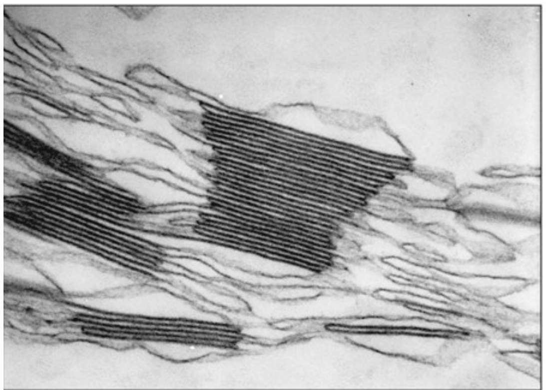
Plastid structure

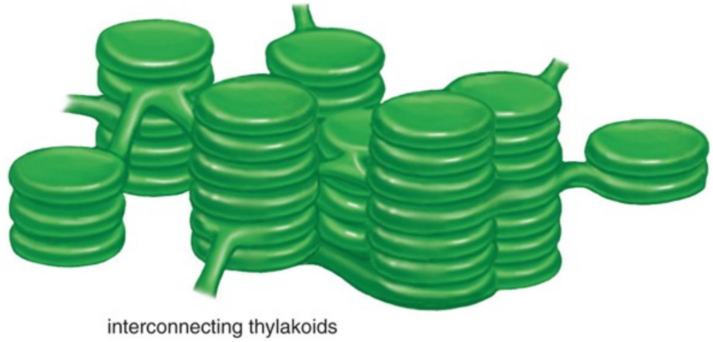
Thylakoids, stroma and starch granules (TEM $\times 37,500$)

Scheme of plastid



Grana



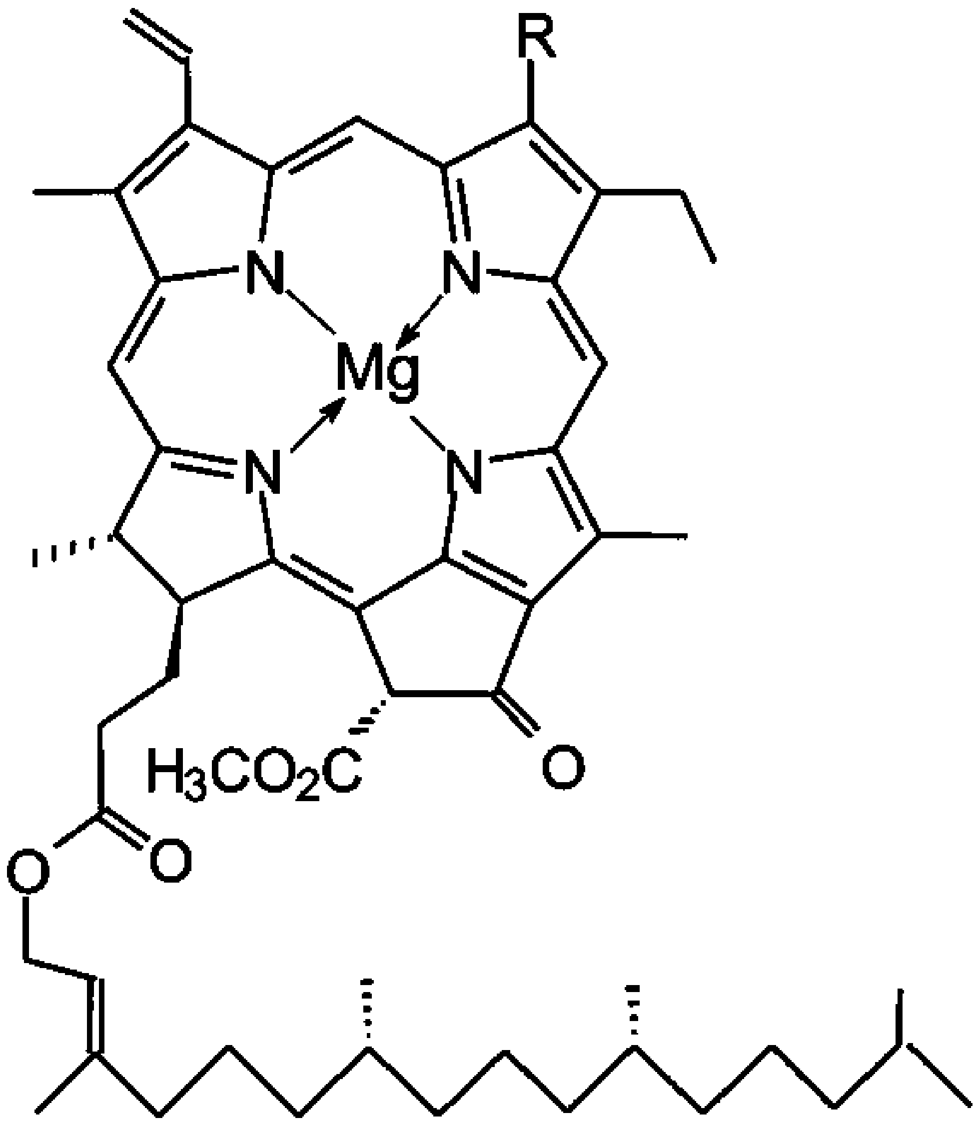


Grana is plural, **granum** singular.

Pigments

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

Chlorophylls *a* and *b*



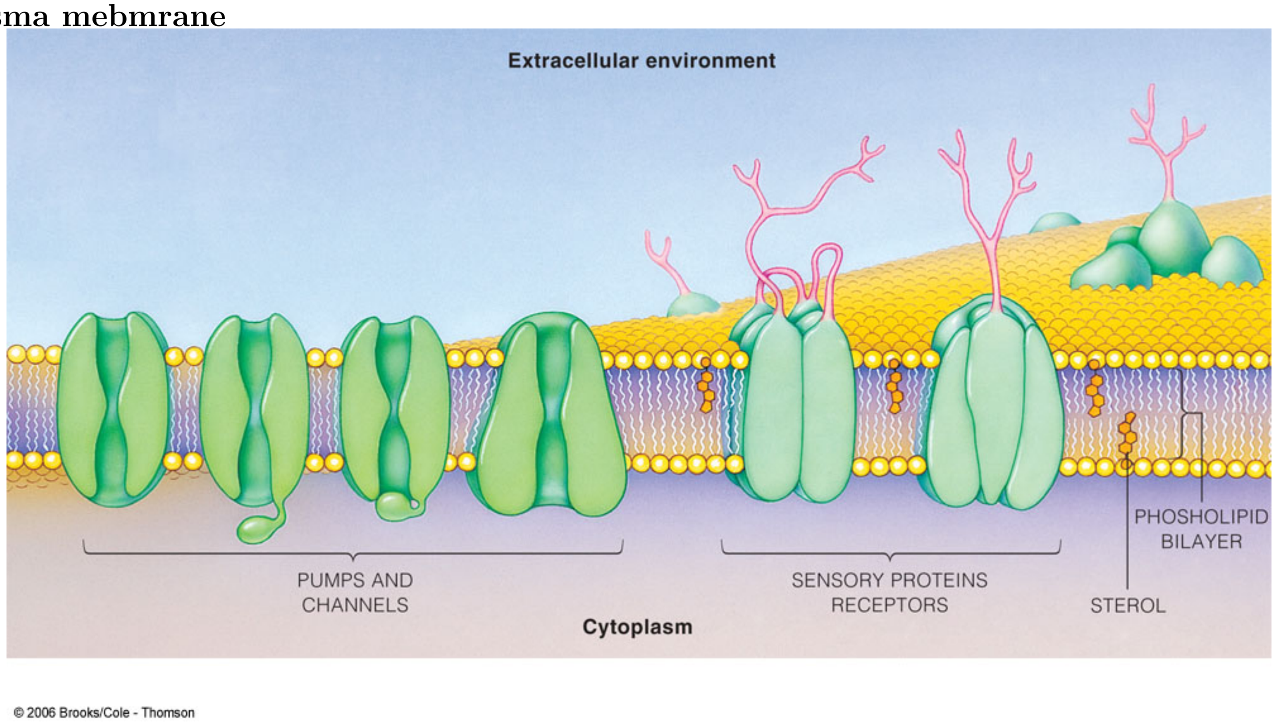
chlorophyll *a* (R = CH_3)
chlorophyll *b* (R = CH=O)

Mitochondria

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

23.2 Cell boundaries

Plasma mebmrane

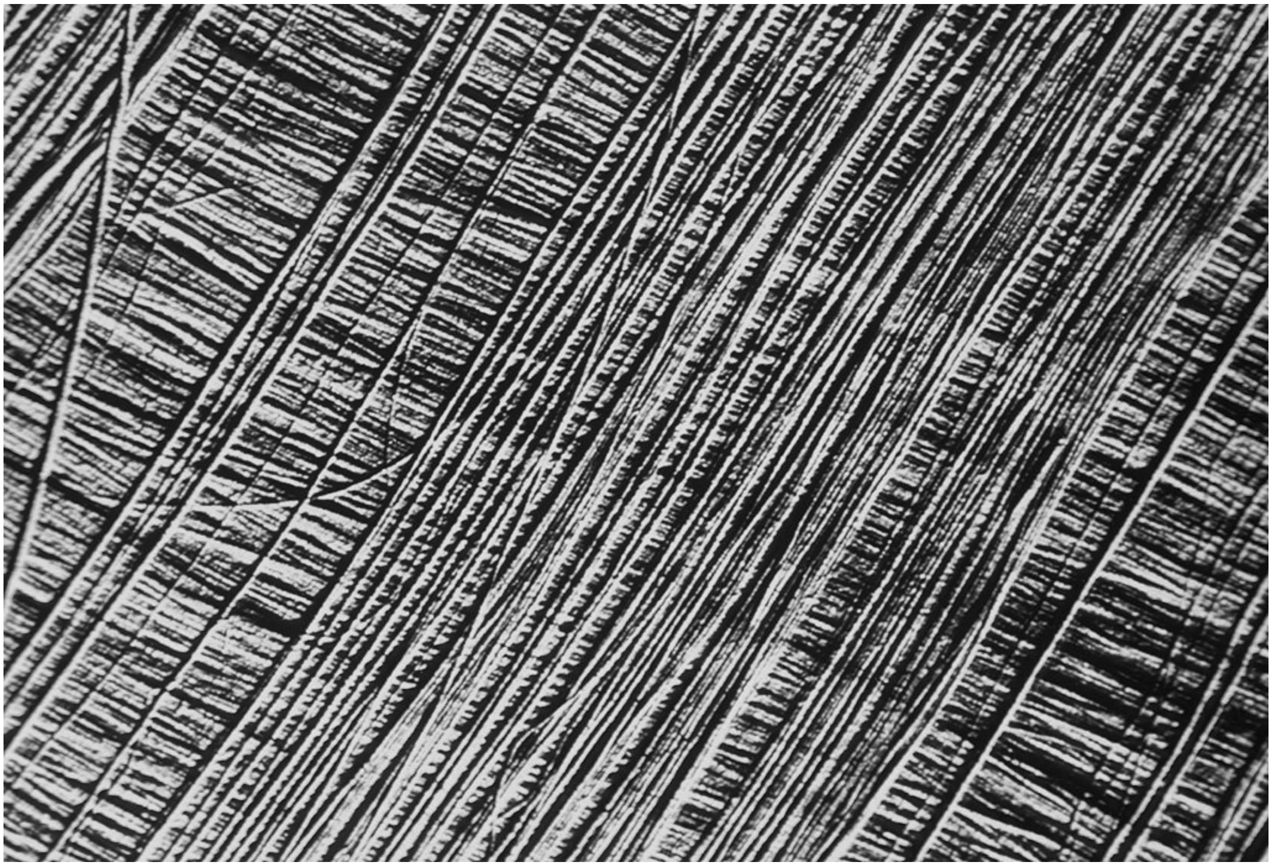


Phospholipids, sterols, proteins: pumps, receptors, channels

Cell wall

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

Fibers

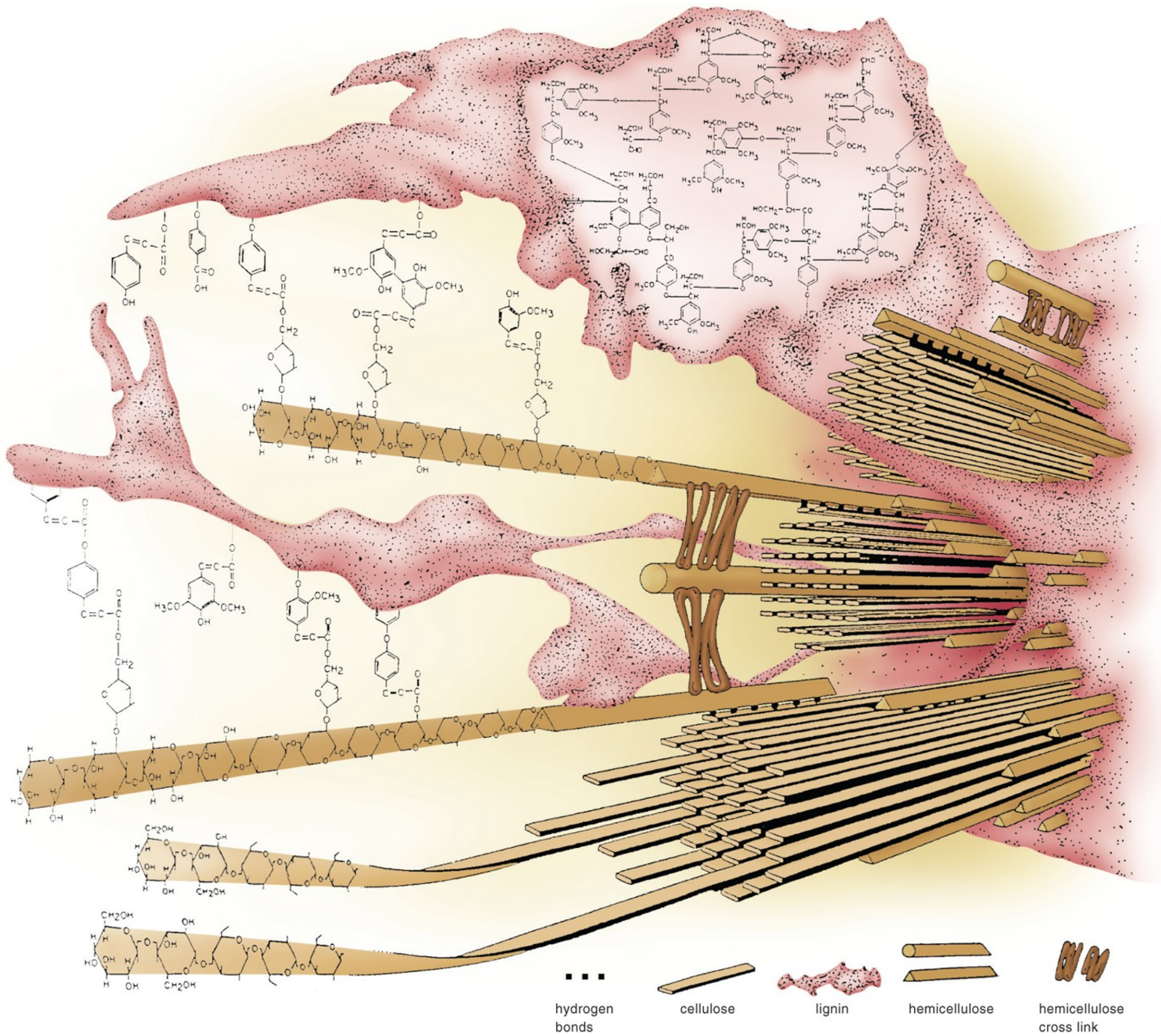


Cellulose fibers in the plant cell wall (SEM)

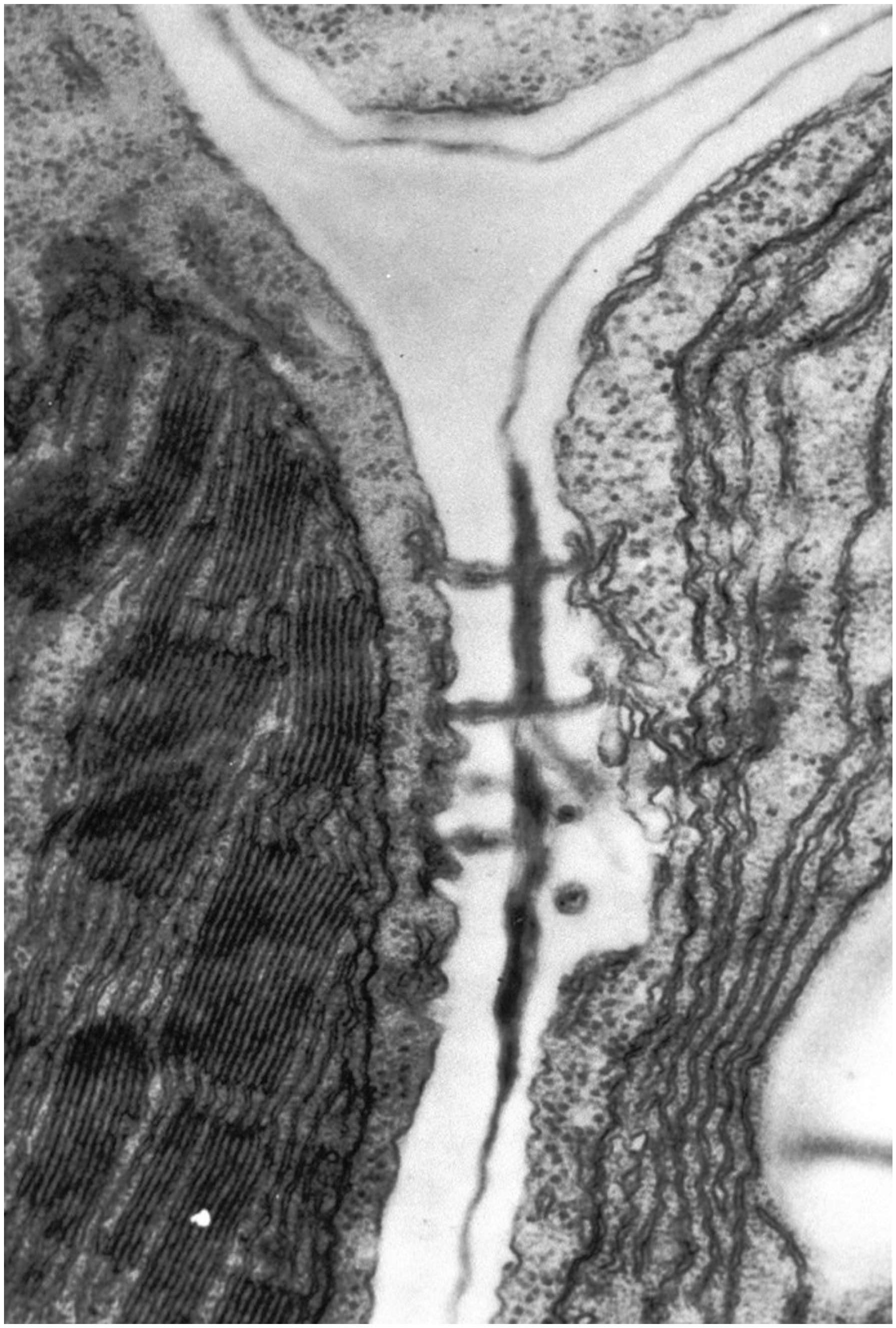
Primary and secondary cell walls

- **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

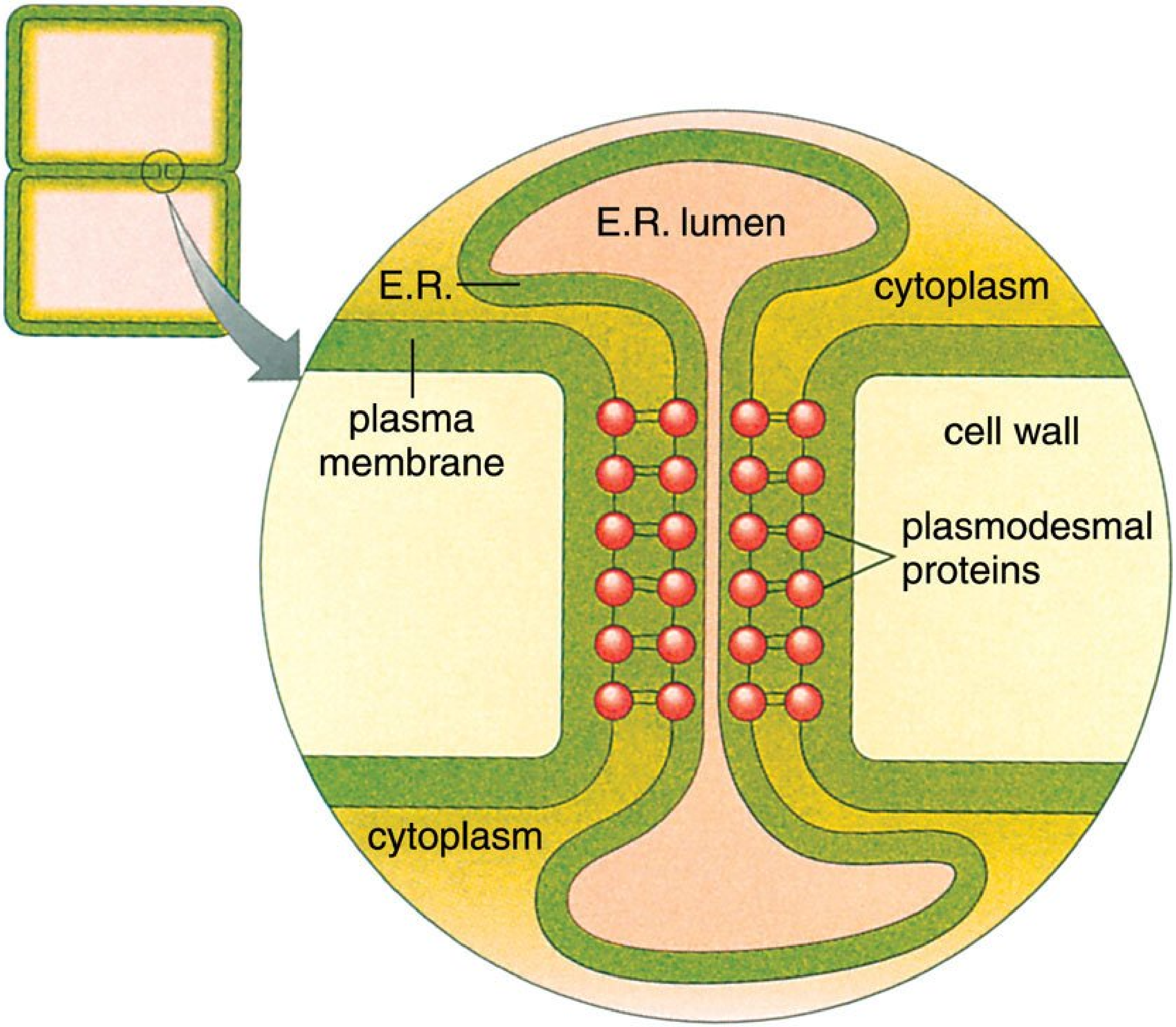


Plasmodesmata



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
- Chloroplasts and mitochondria are both results of symbiogenesis
- Secondary cell walls cover dead cells

For Further Reading

References

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

Outline

24 Questions and answers

24.1 Quiz

Quiz question (... points)

...

- ...

25 Plant cell

25.1 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**

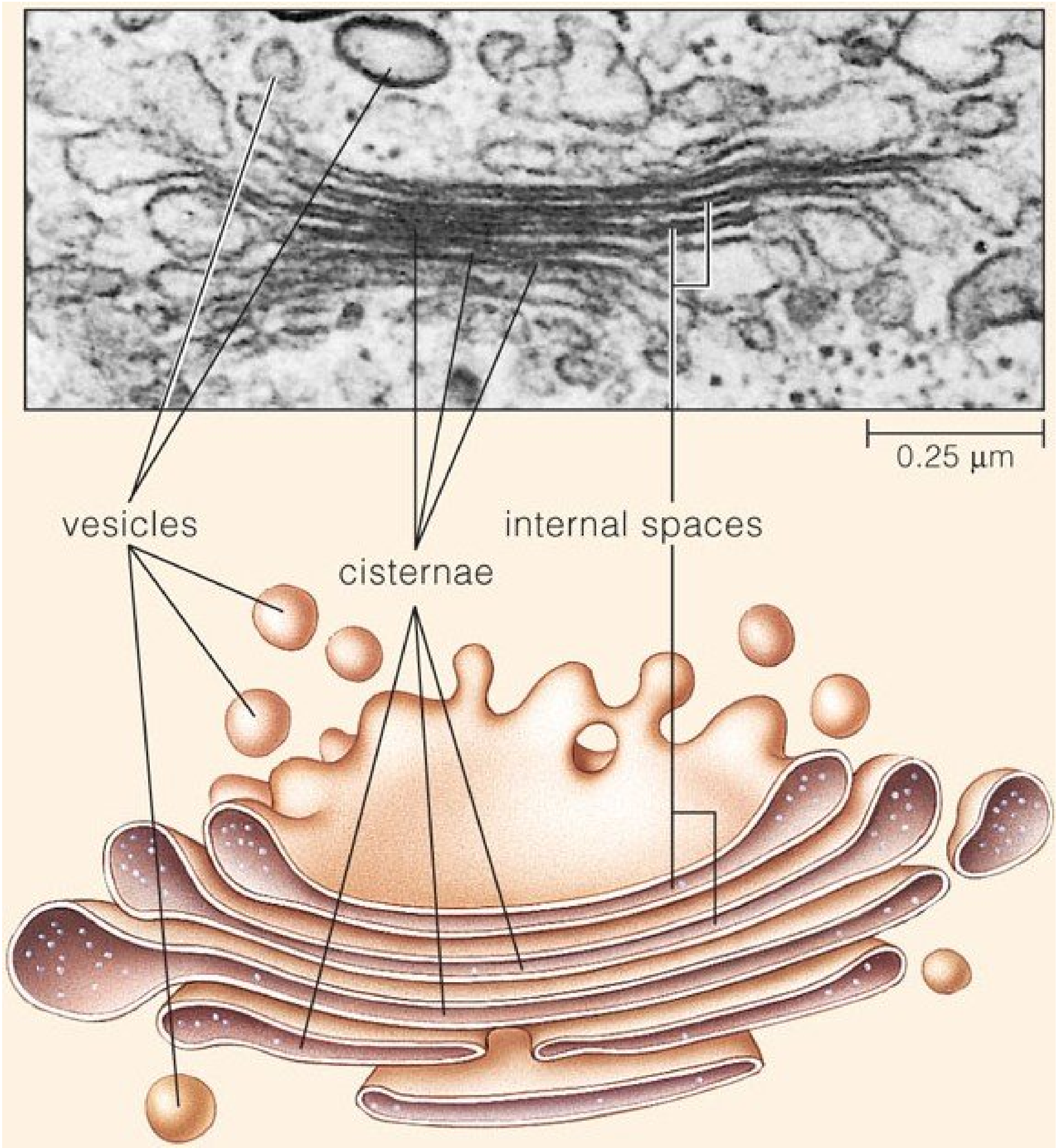
Symplast and apoplast

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

Endoplasmatic reticulum (network), ER

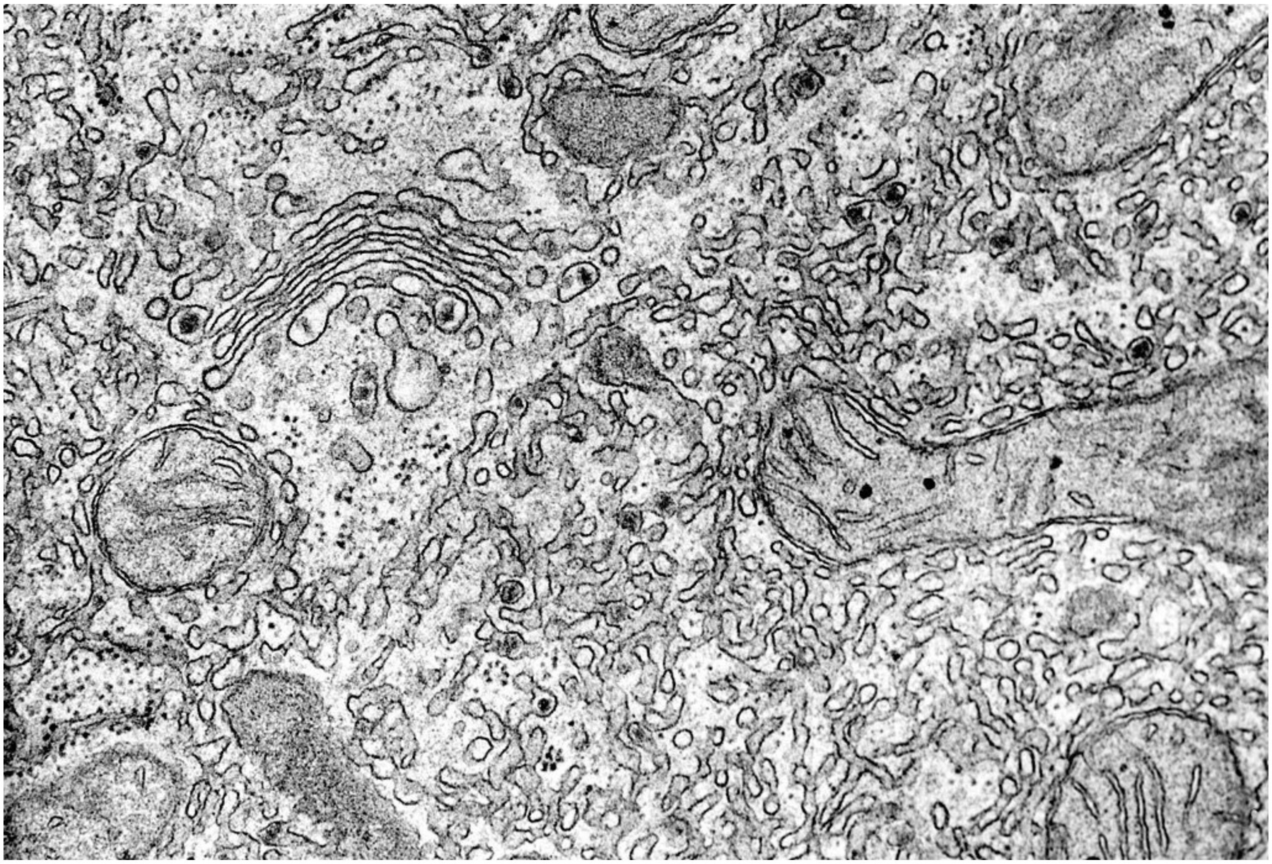
Rough endoplasmic reticulum with ribosomes along outer surface. Manufactures many proteins destined for secretion or for incorporation into membranes (TEM)

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)

25.2 Protein synthesis

Nucleus structure

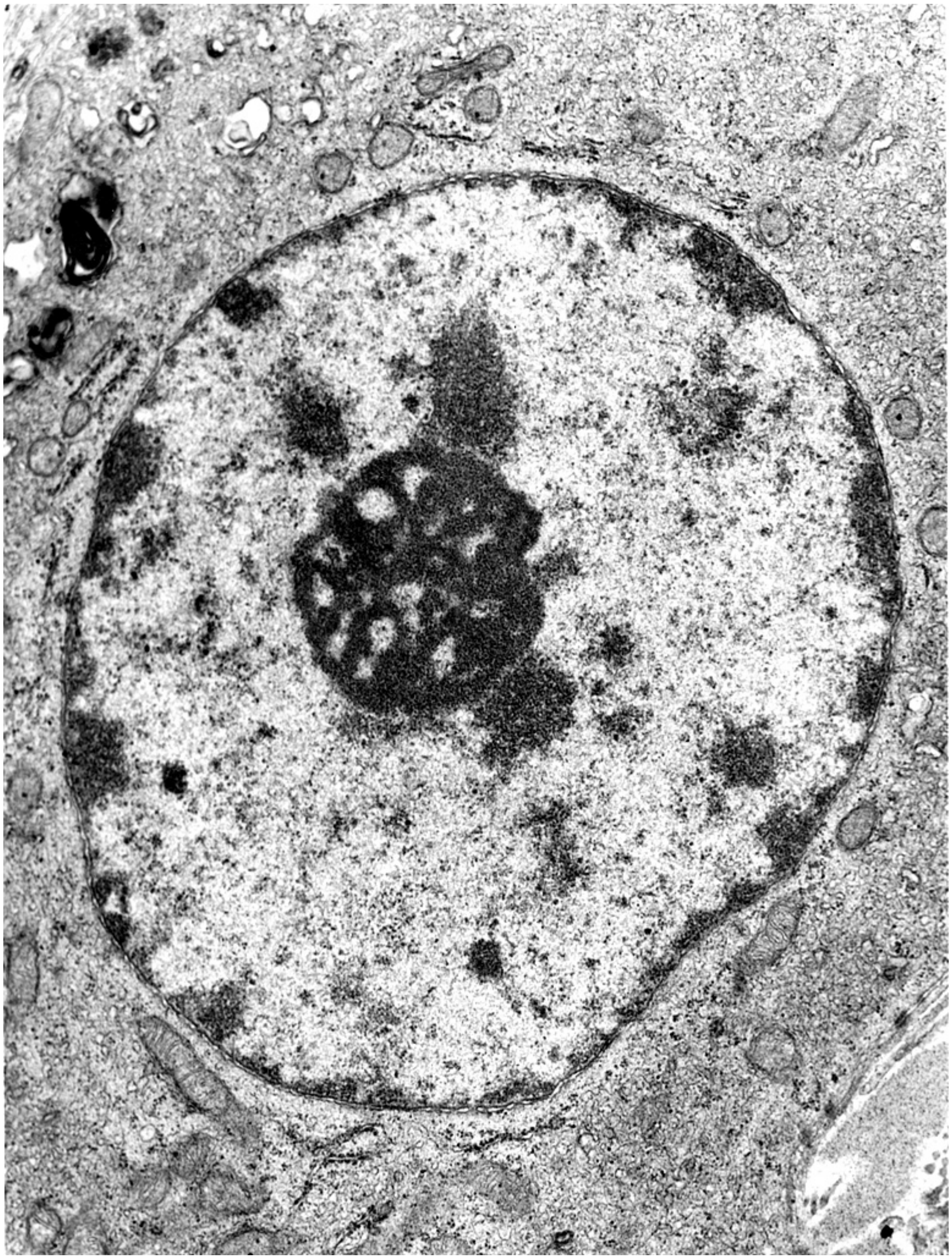
Nuclear envelope Double layered membrane, filaments of protein lamin line inner surface and stabilize structure, inner and outer membranes connect to form pores

Nucleoplasm Portion inside the nuclear envelope

Nucleoli Dark staining bodies within nucleus, site for ribosome synthesis

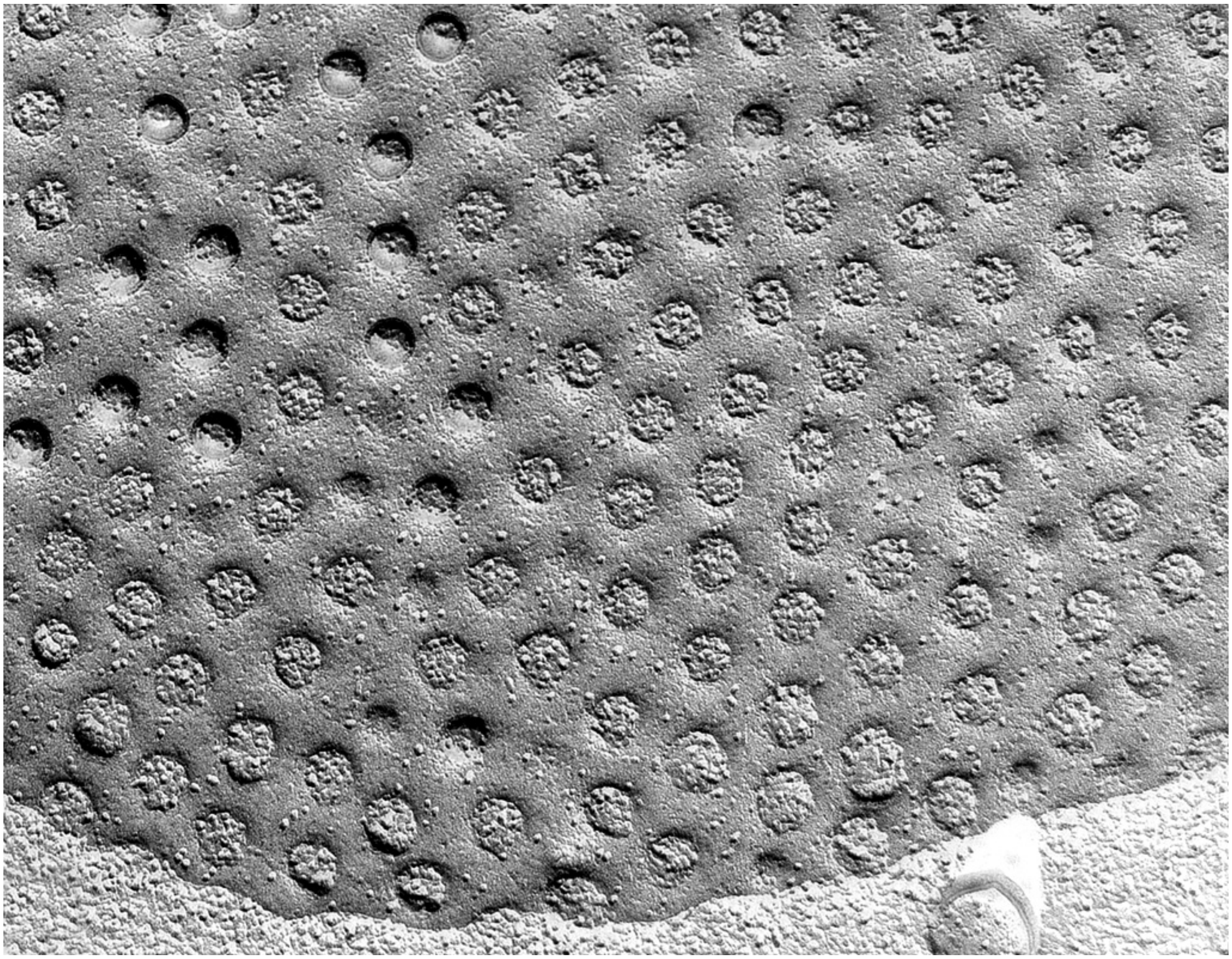
Chromosomes Store genetic information in nucleotide sequences, each chromosome consists of chain of nucleosomes (long DNA molecule and associated histone proteins). When cell is not dividing, chromosomes are frequently seen as **chromatin**.

Nucleus



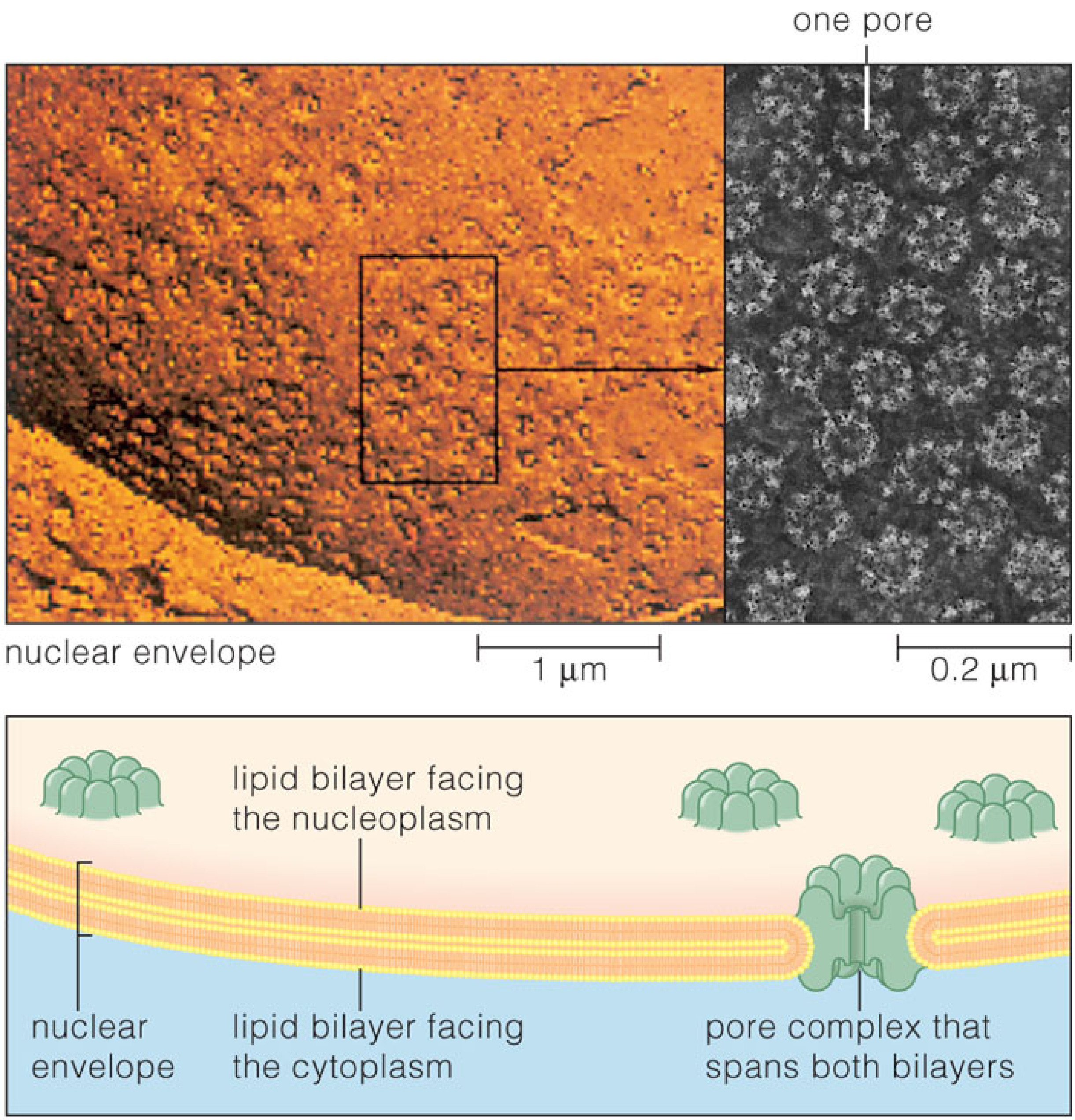
A typical nucleus with a prominent nucleolus (TEM).

Nuclear pores

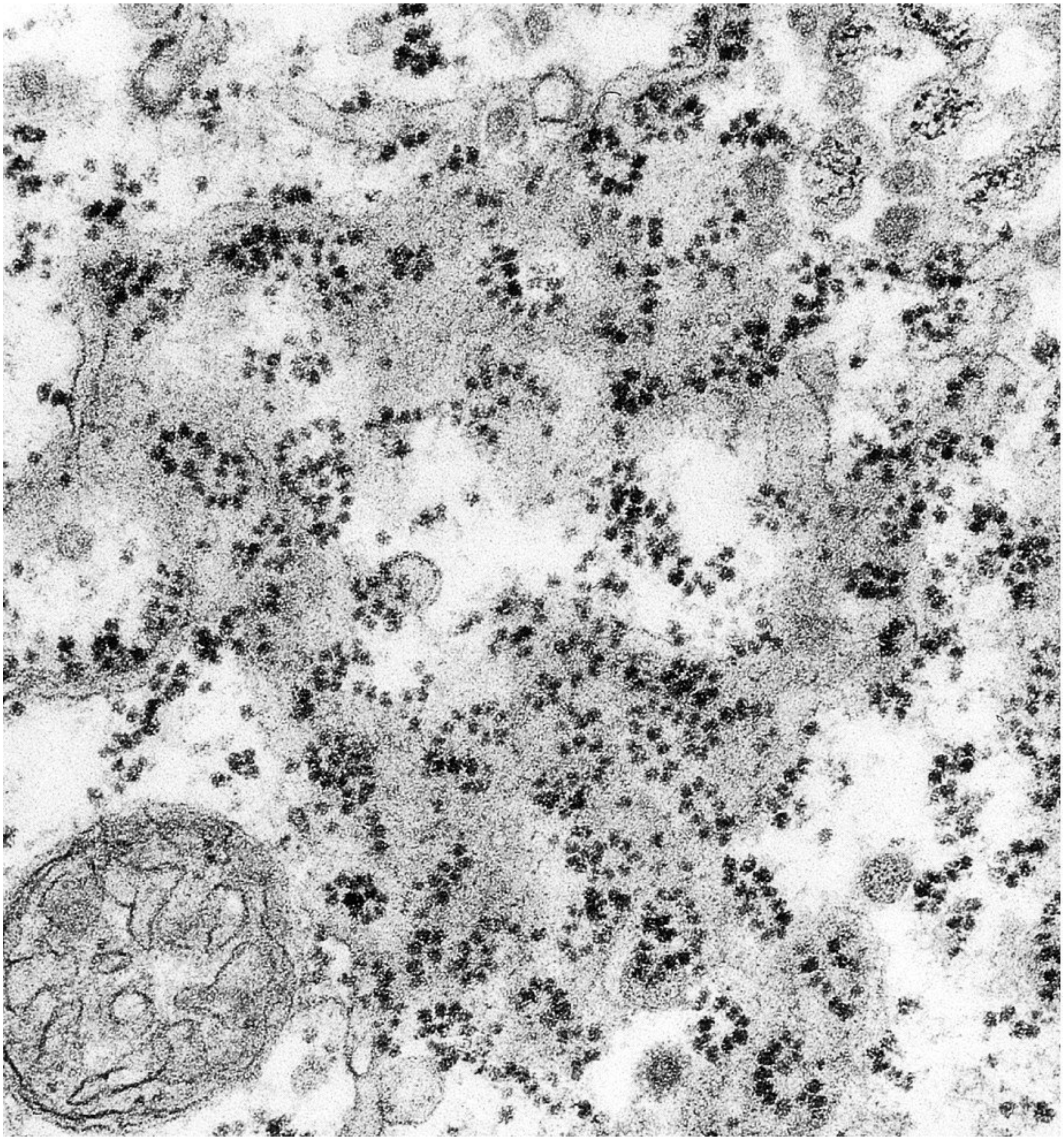


Freeze-fracture technique used to show nuclear pores. Nuclear pores are structures in the nuclear envelope that allow passage of certain materials between the cell nucleus and the cytoplasm (TEM $\times 100,000$)

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



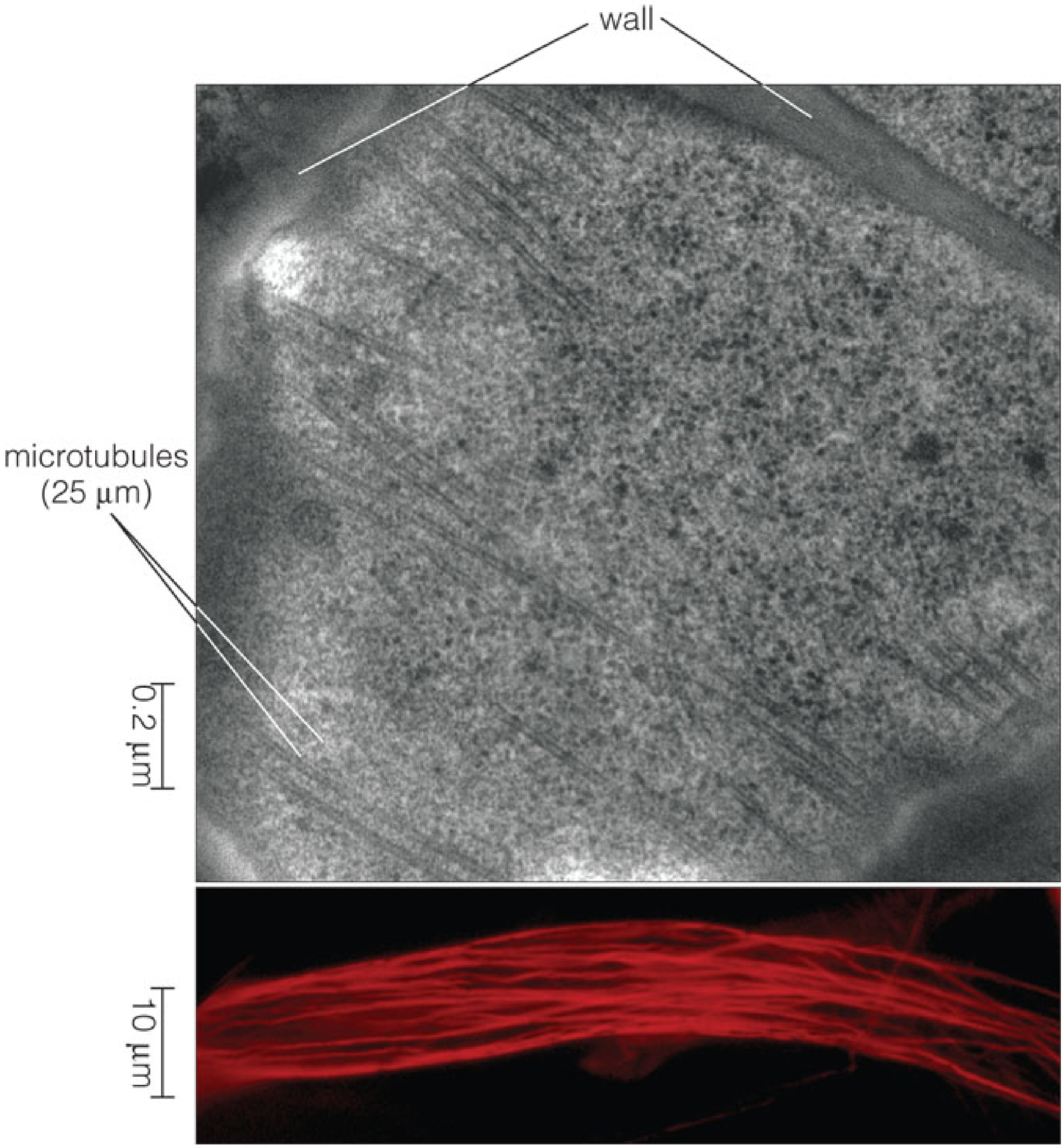
25.3 Other cell structures

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



26 Mitosis and meiosis

26.1 Mitosis

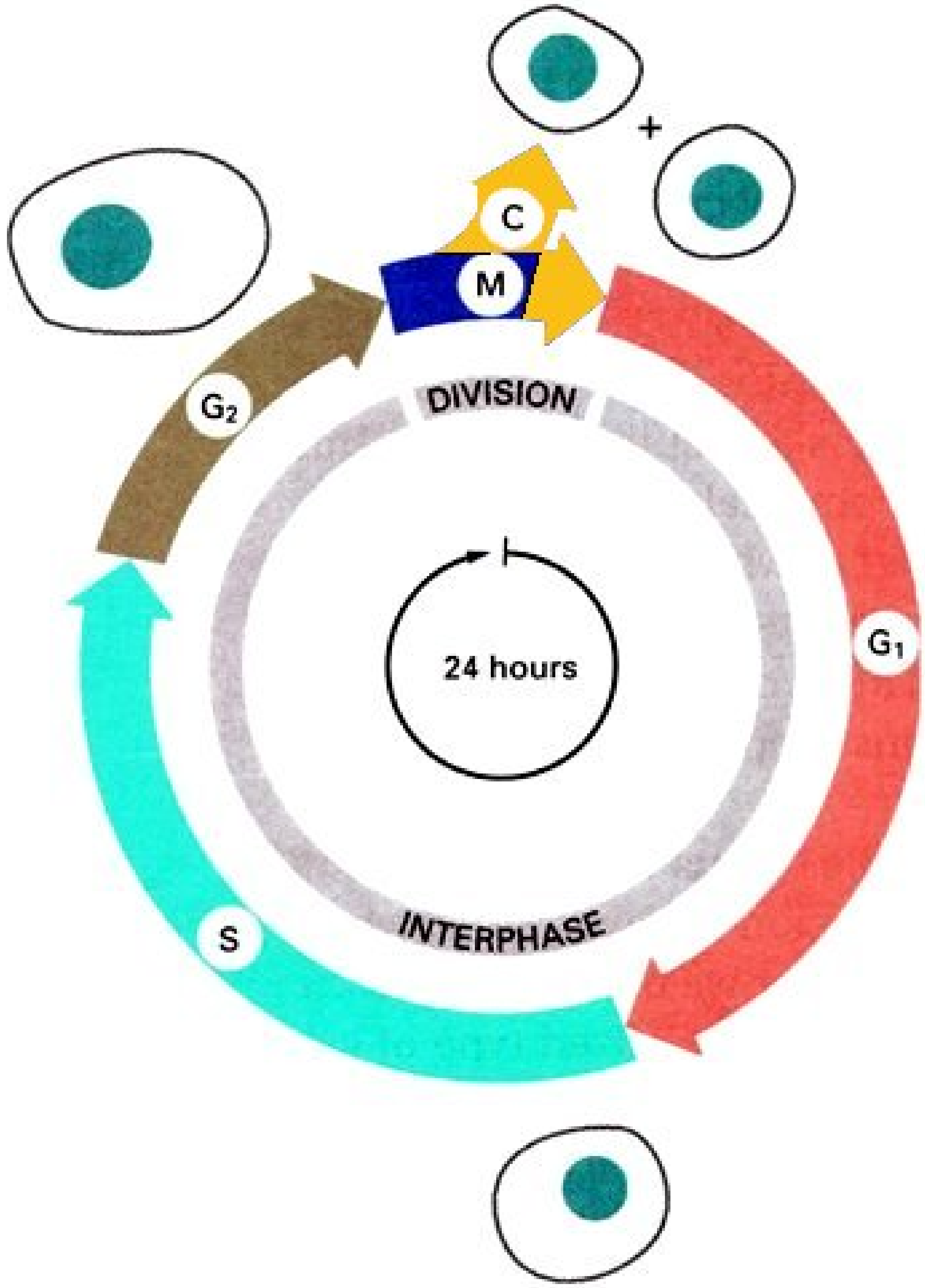
Definition of mitosis

- *Equal cell division, where each of daughter cells receives the same number of chromosomes as a mother cell*
- Chromosome formula: $\mathrm{X} \longrightarrow \mathrm{I} + \mathrm{I}$
- **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

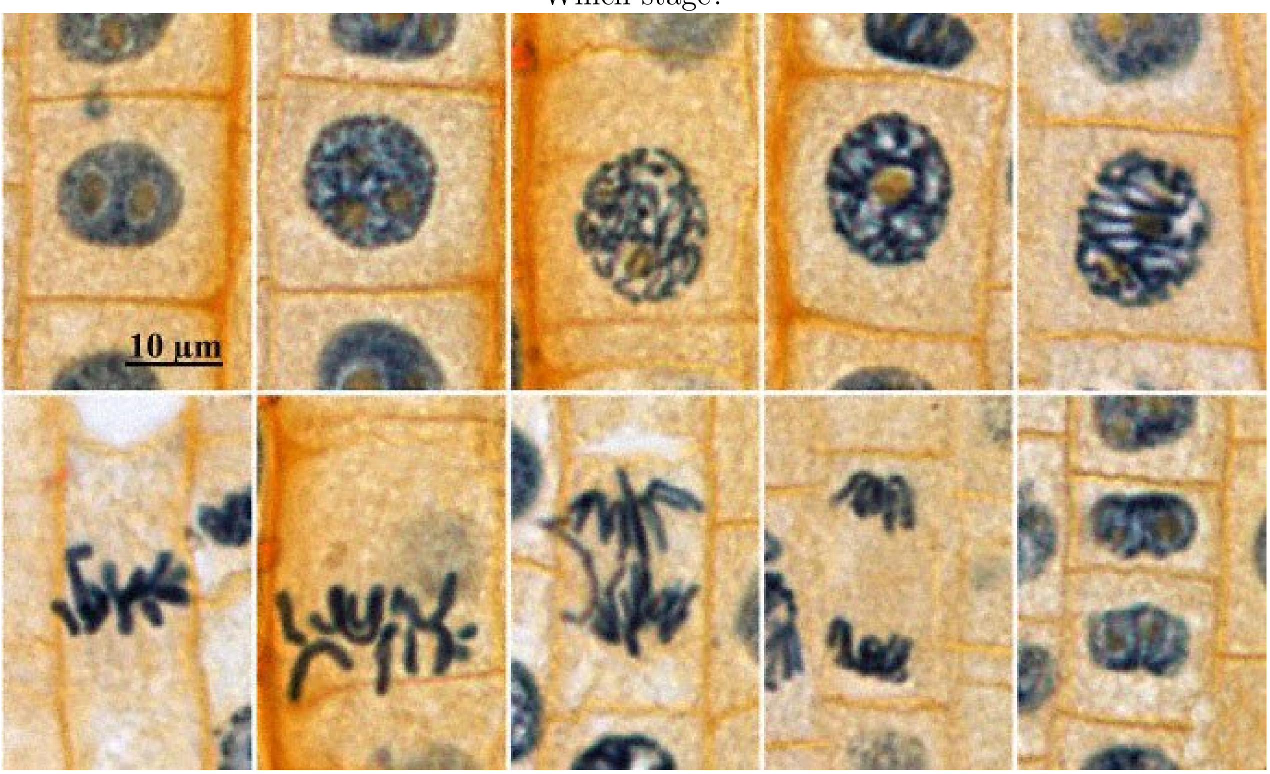
  - Prophase
  - Metaphase
  - Anaphase
  - Telophase
- Cytokinesis

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

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

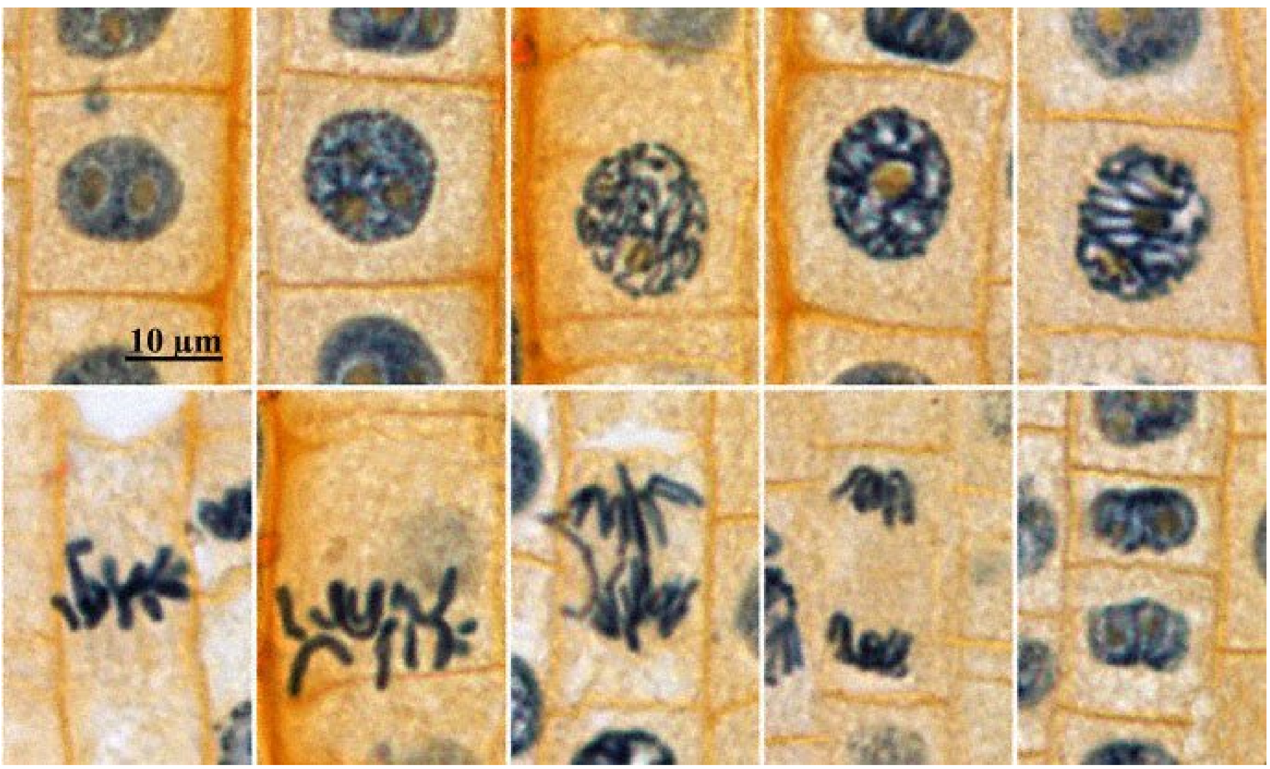
Outline

27 Questions and answers

27.1 Quiz

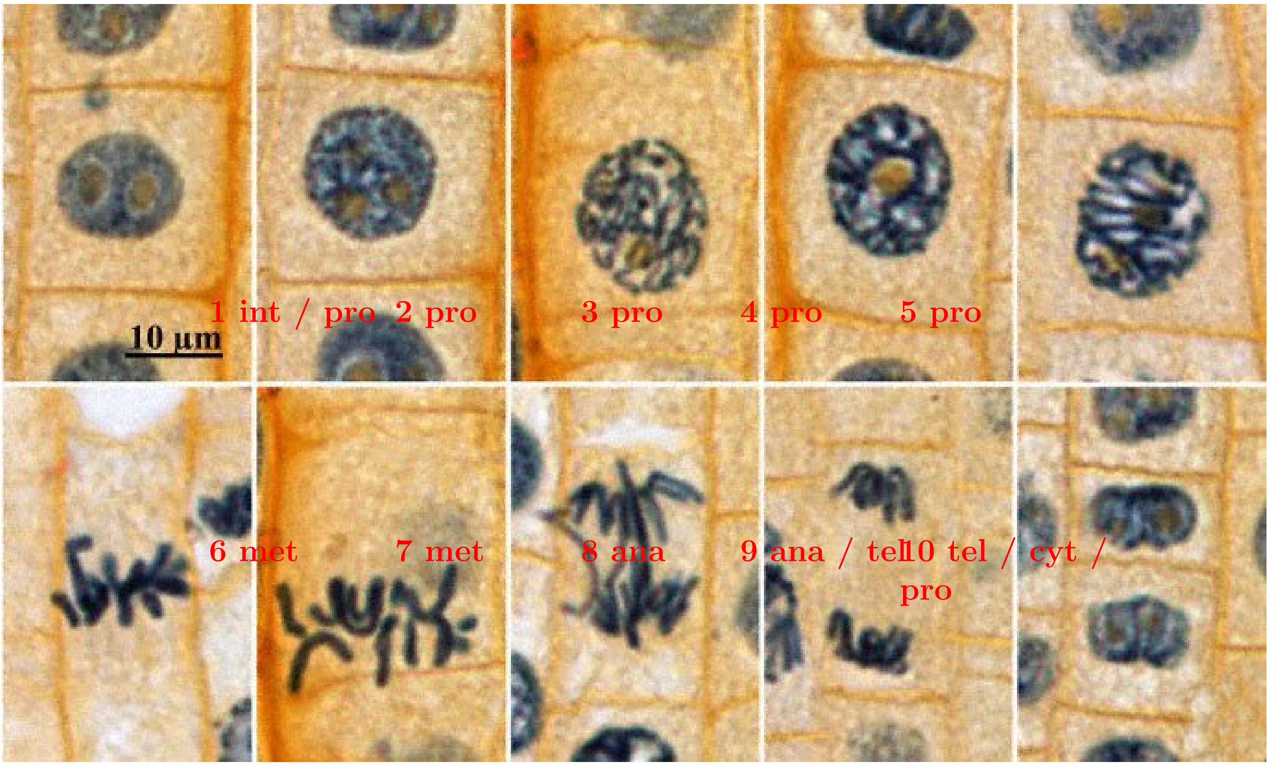
Final question (2 points)

Which stage?



Final question (2 points)

Which stage?



28 Mitosis and meiosis

28.1 Syngamy (Y!)

Why do living things support diversity

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

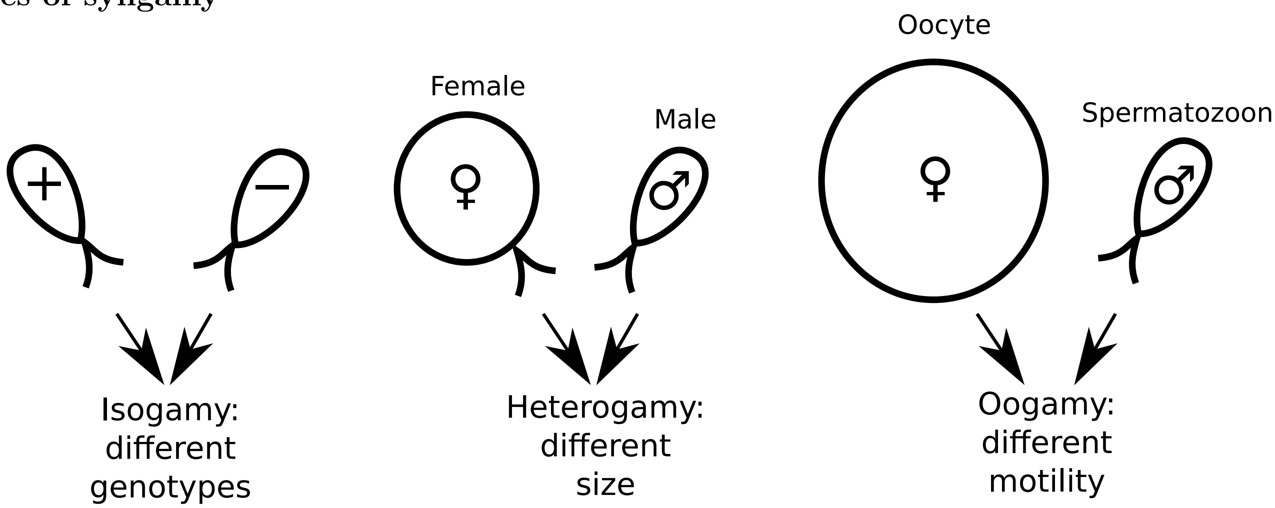
Exchange and renovation of DNA

- 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



28.2 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

29 Questions and answers

29.1 Quiz

Quiz question (... points)

-
-

30 Life cycle

30.1 Syngamy and meiosis

Some useful terms: checklist

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

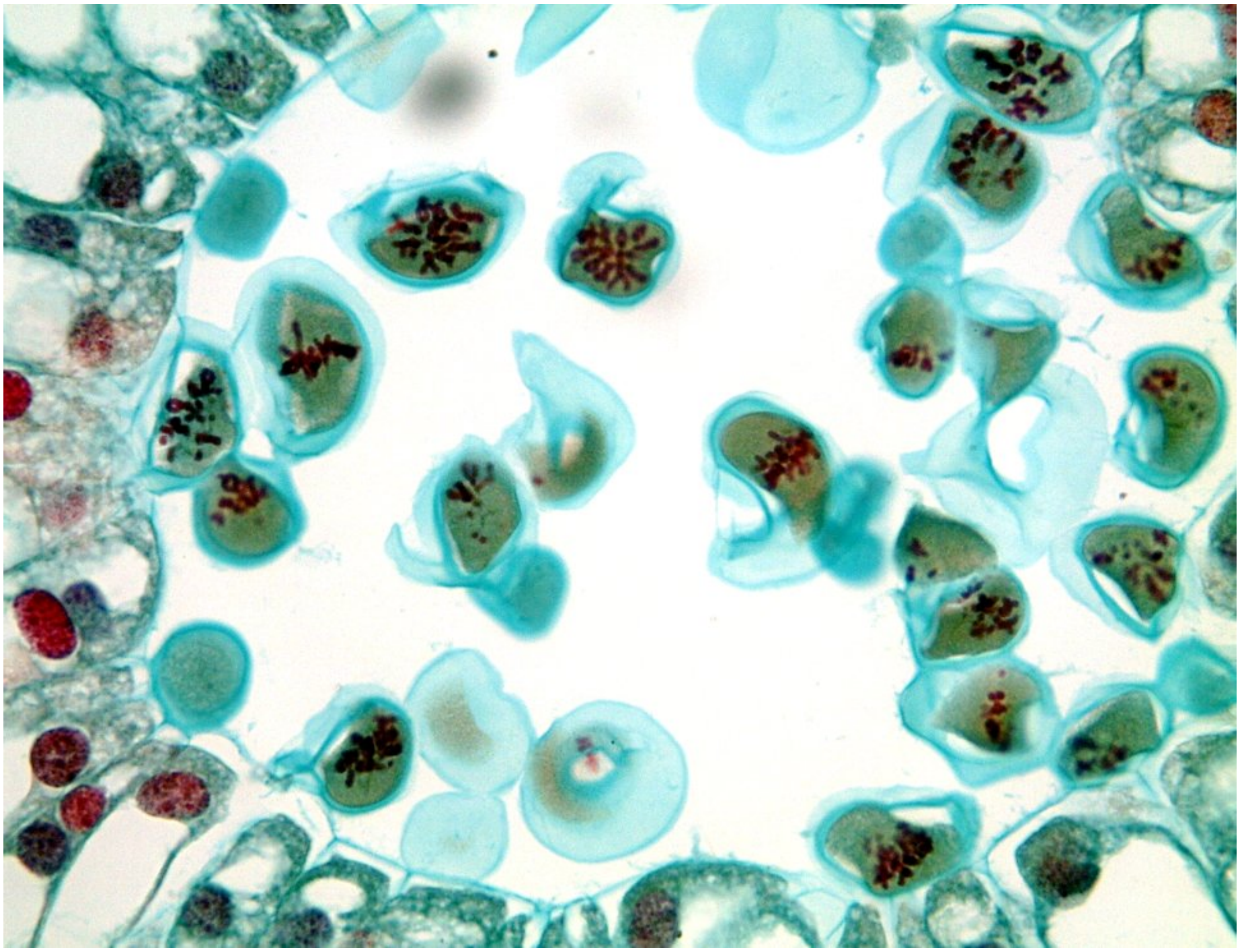
Ploidy, or chromosome set

- 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: $2n \longrightarrow n + n$

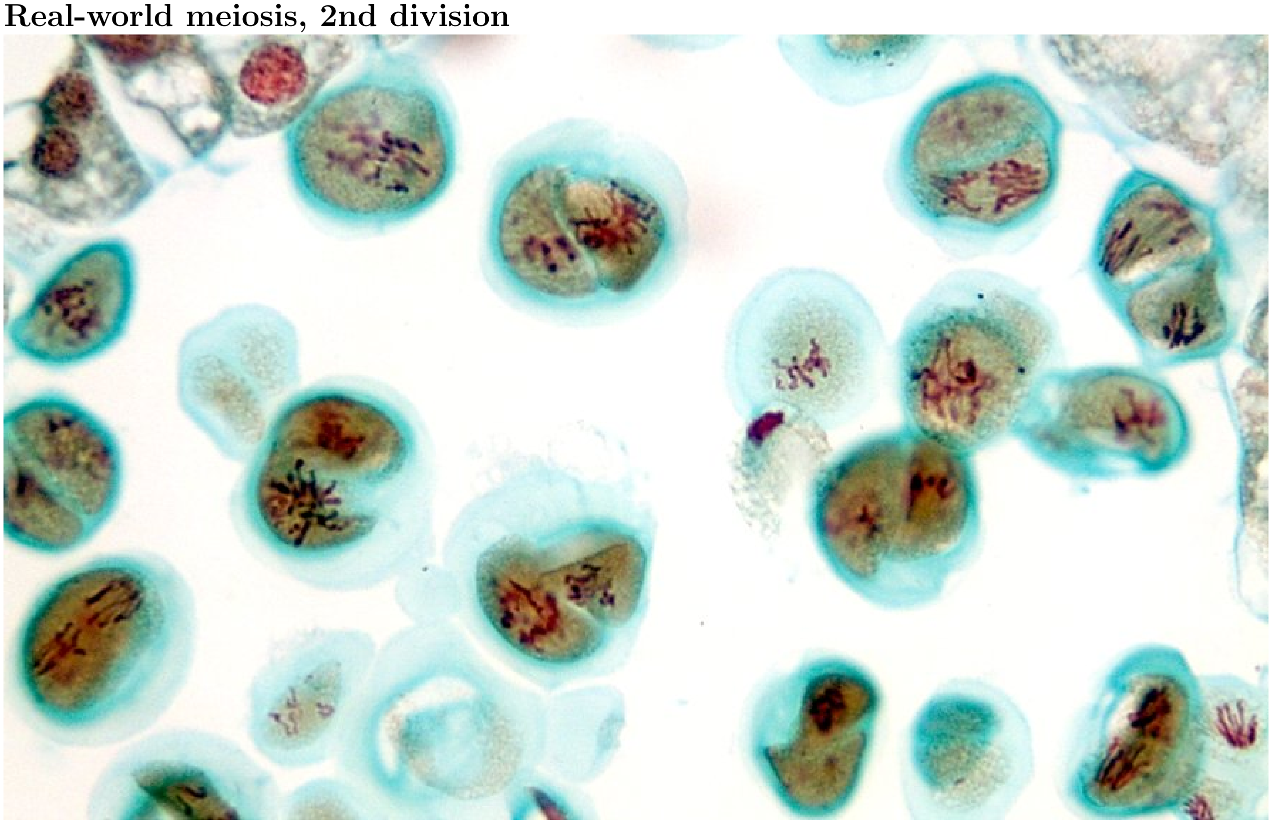
Stages of meiosis

- 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

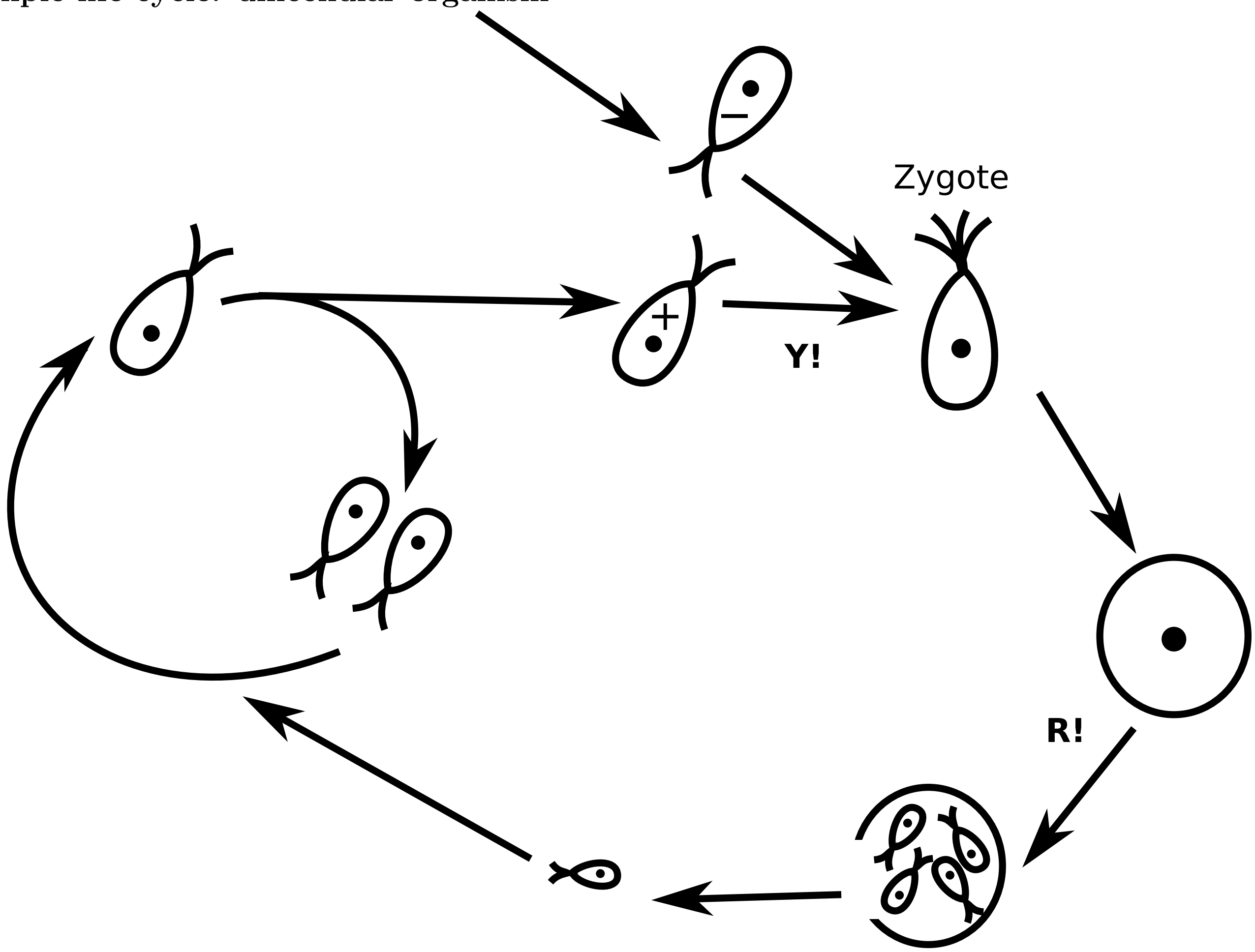


Polyploids

- 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**

30.2 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

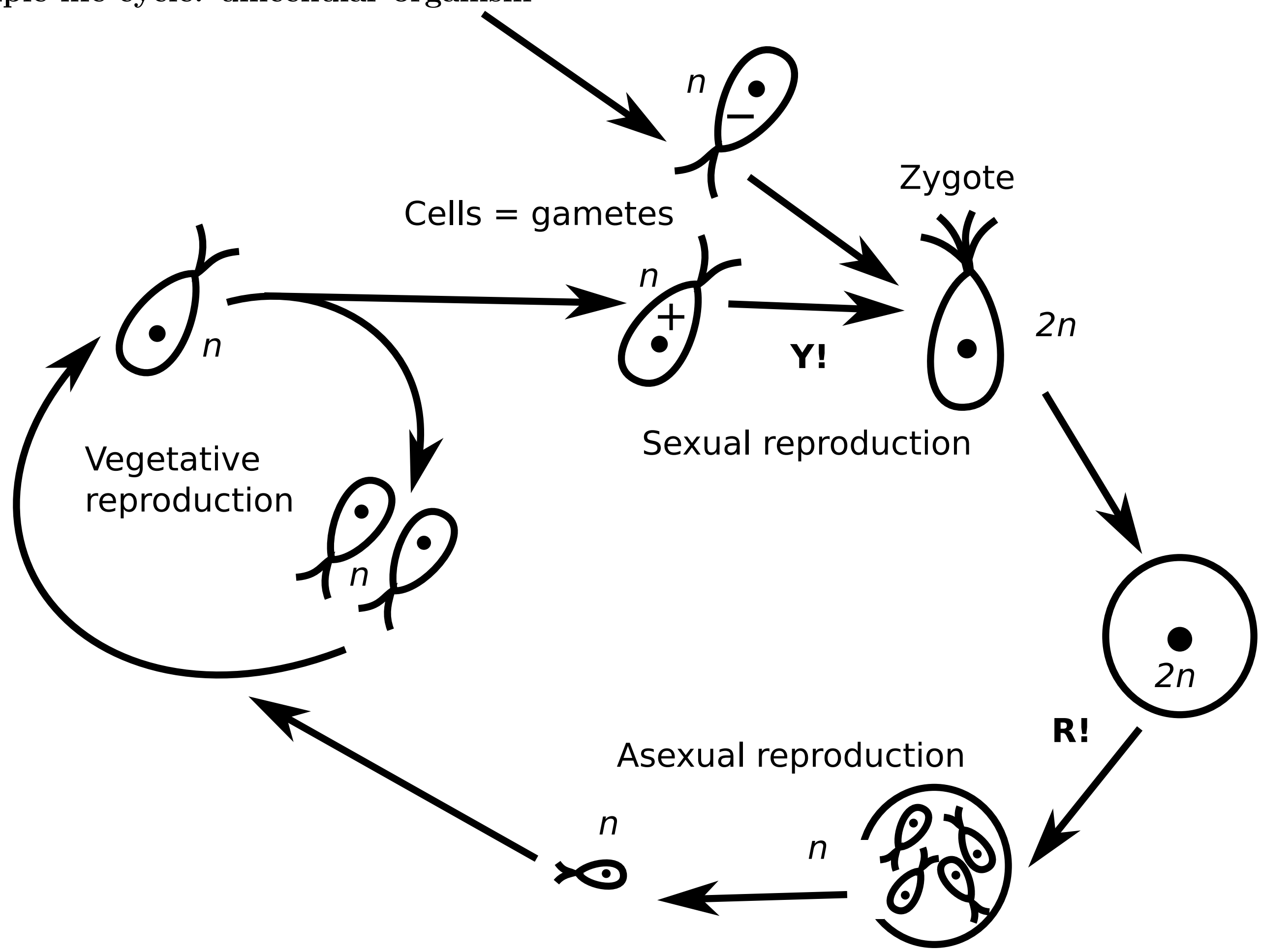
[1] A. Shipunov. *Introduction to Botany* [Electronic resource]. Mode of access: `http://ashipunov.info/shipunov/school/biol_154`

Outline

31 Life cycle

31.1 Basics of life cycles

Simple life cycle: unicellular organism

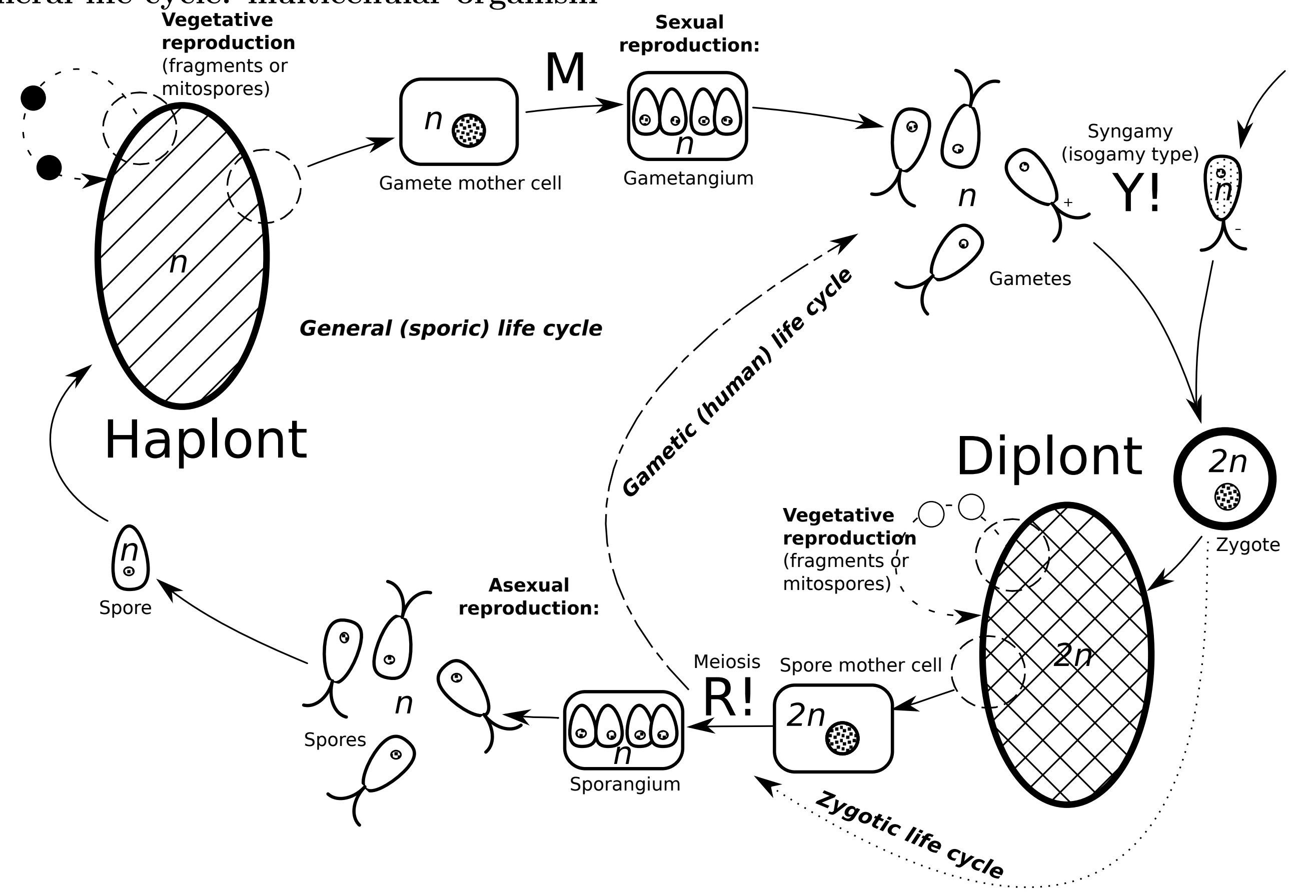


Associated terms: mitosis, meiosis (R!), syngamy (Y!), reproduction, sexual reproduction, asexual reproduction, vegetative reproduction, isogamy, heterogamy, oogamy, zygote, gamete, male, female, spermatozoon, oocyte

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

References

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

Outline

32 Questions and answers

32.1 Quiz

Quiz question (2 points)

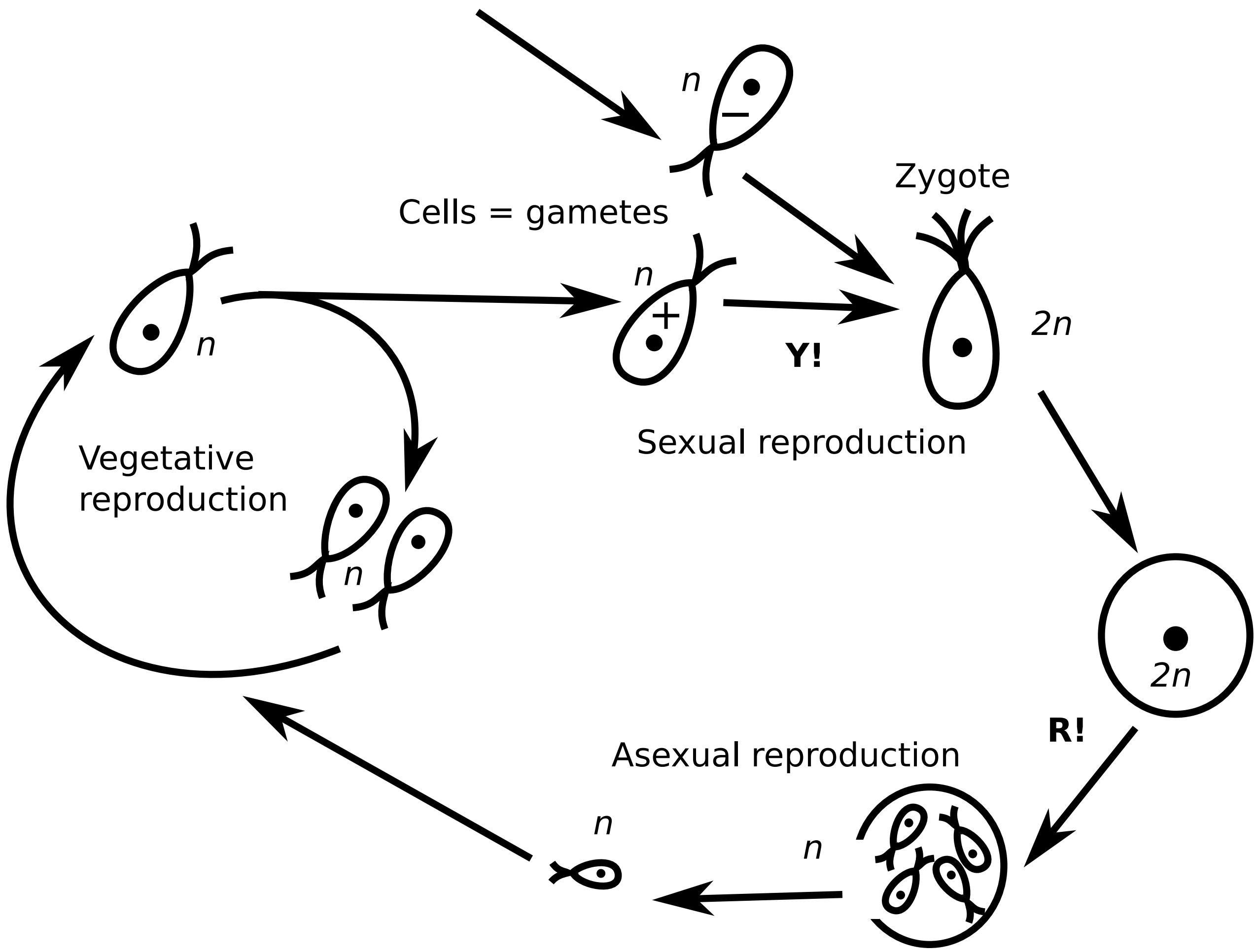
Why is multicellularity better?

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

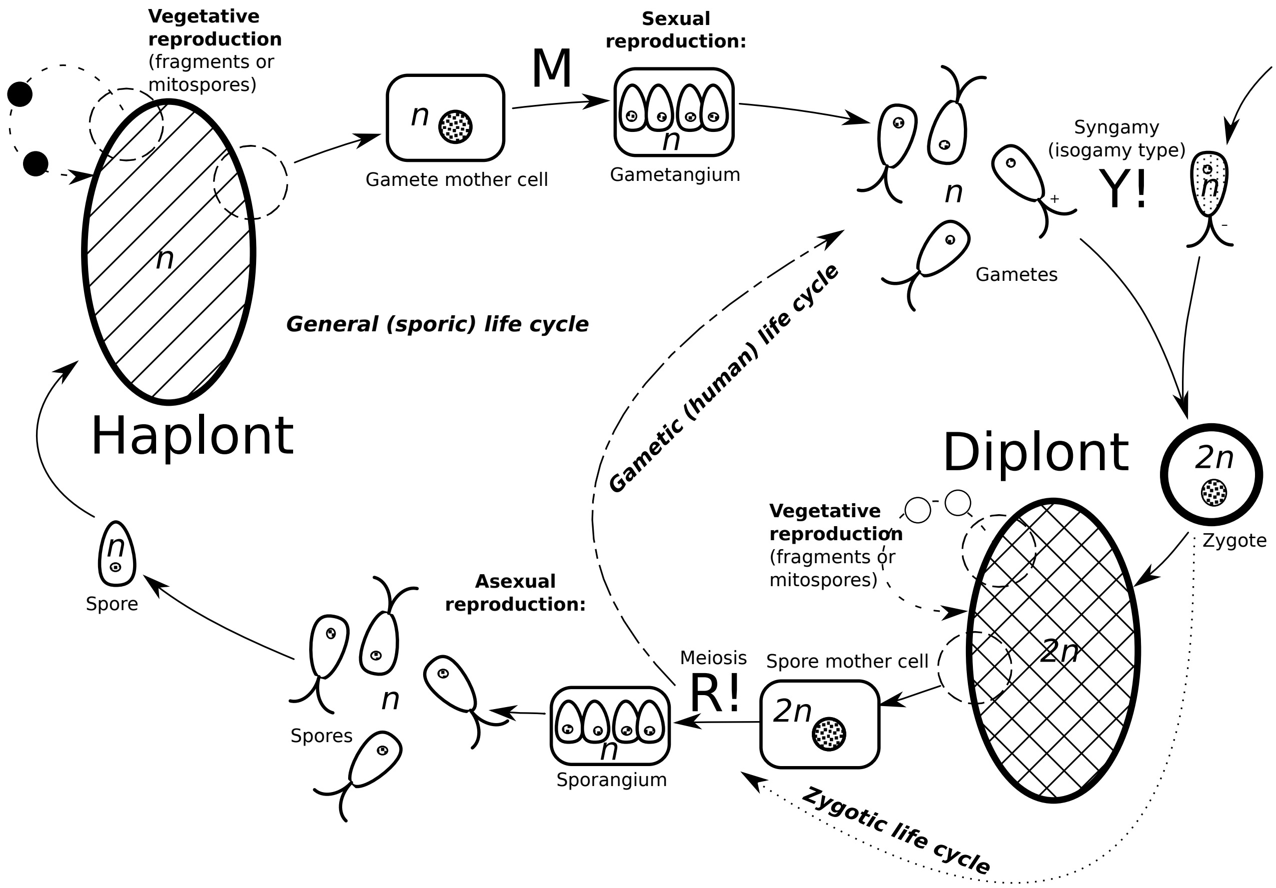
33 Life cycle

33.1 Basics

General life cycle: unicellular organism



General life cycle: multicellular organism

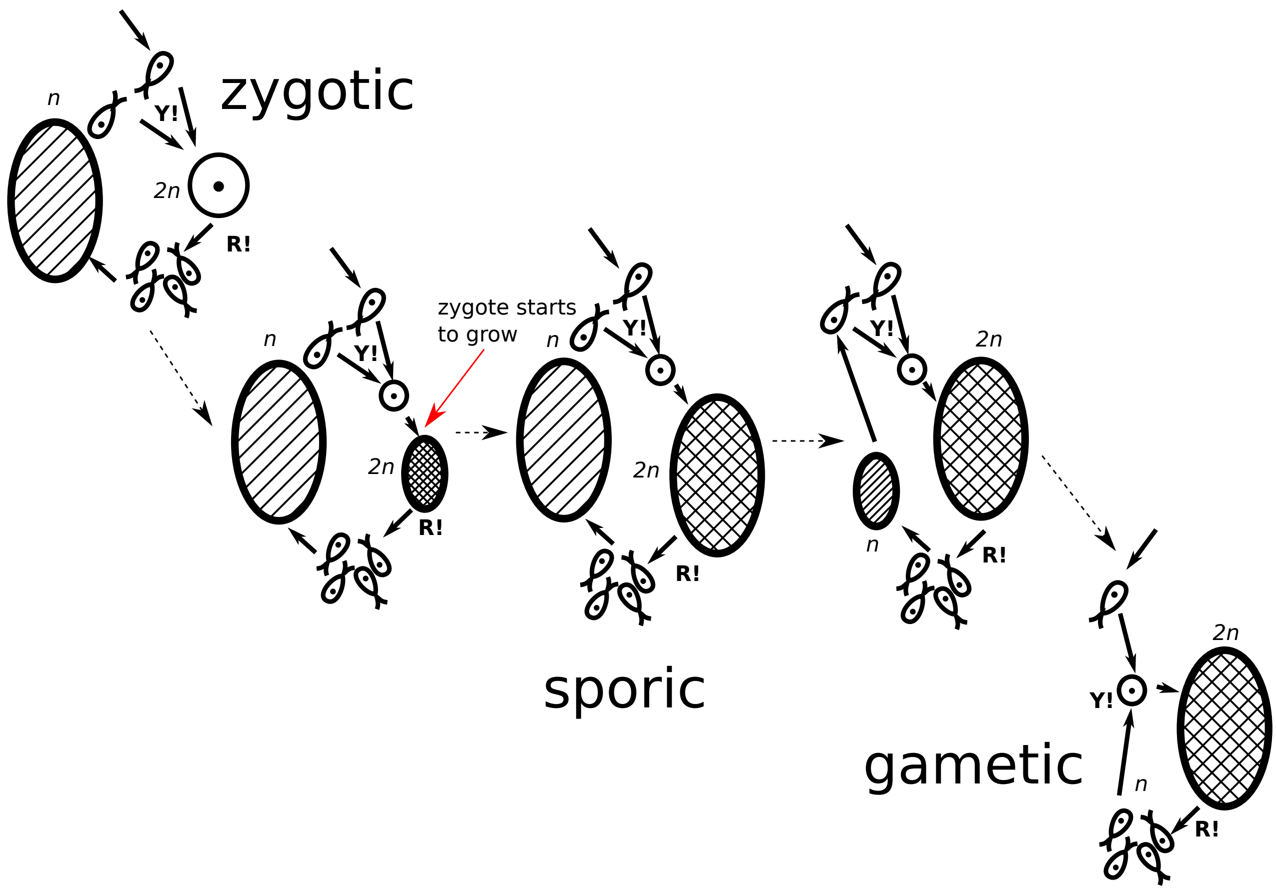


33.2 Evolution of life cycles

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!

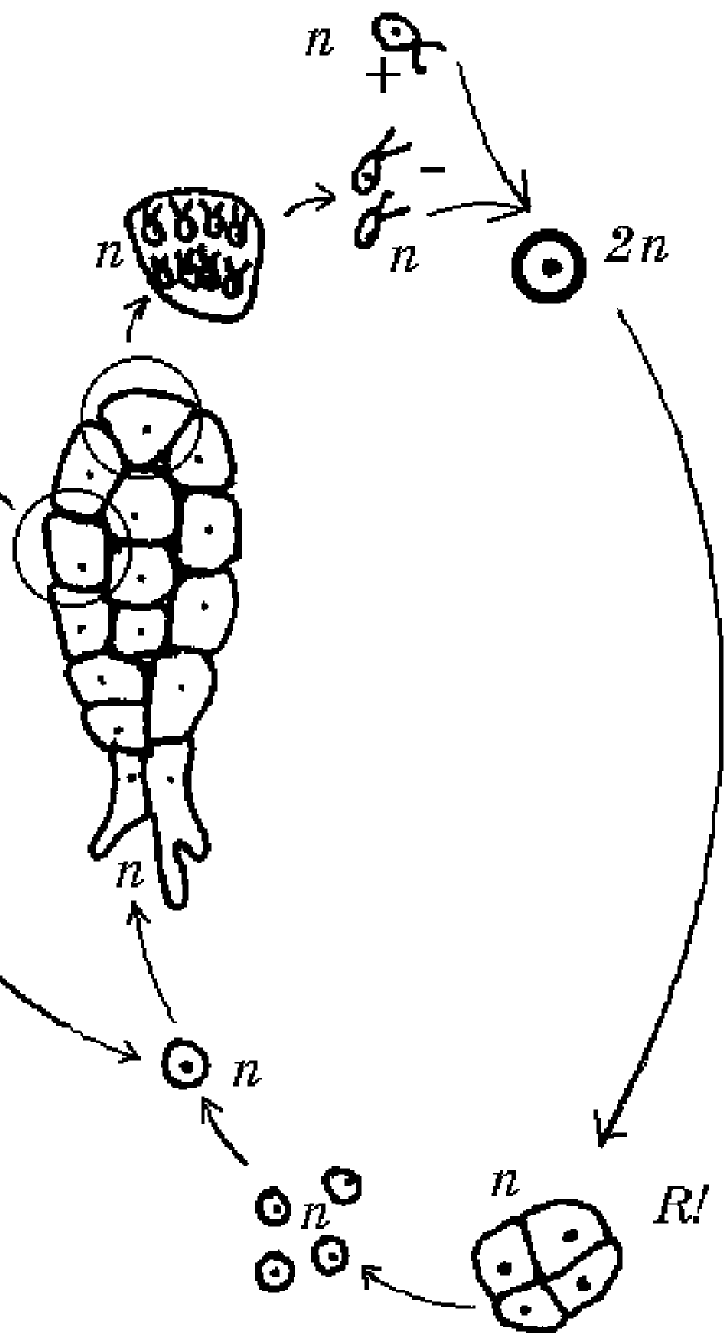
A. **Dominance**: if one gene is deadly mutated, there is the second working variant

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

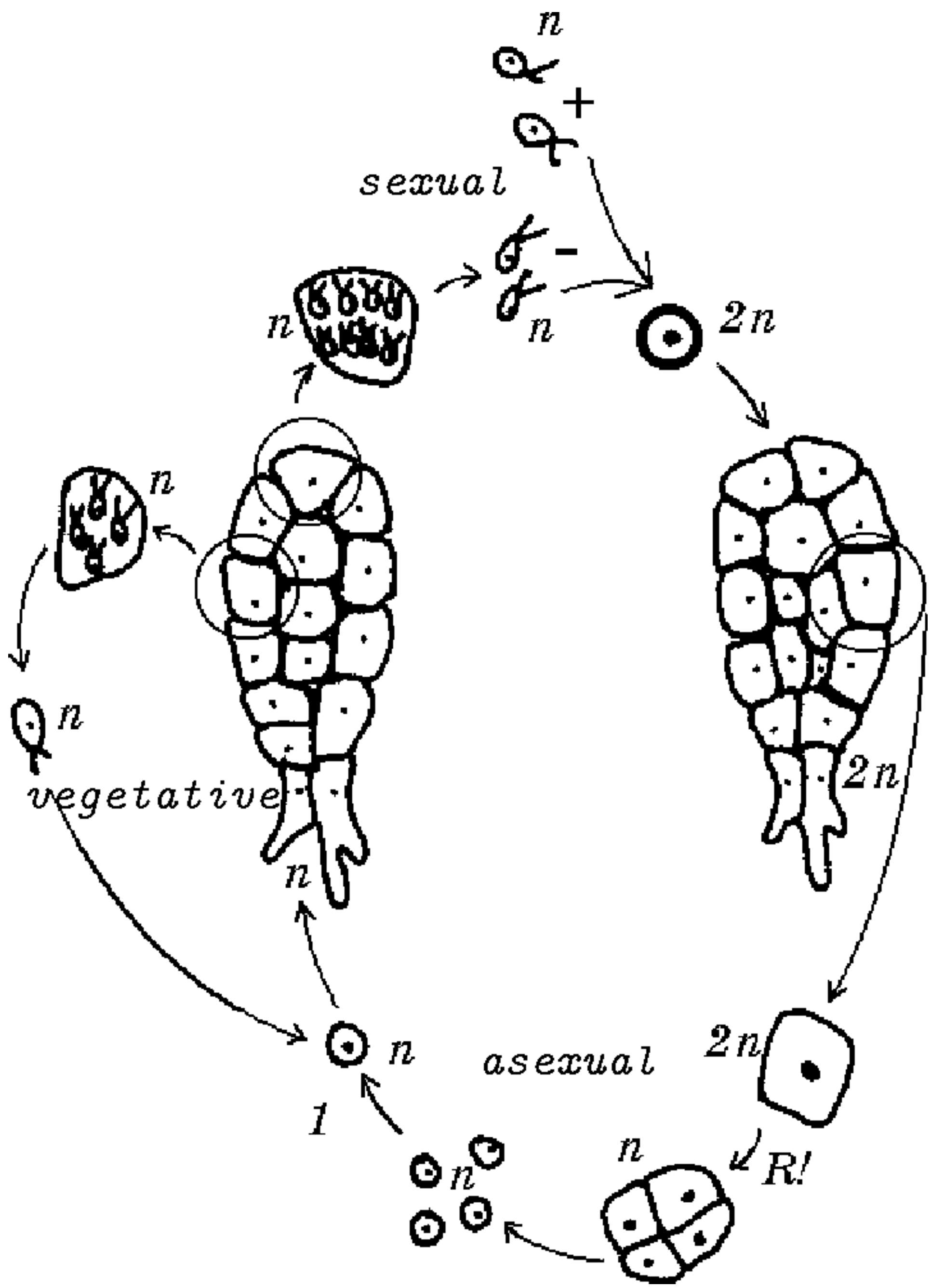
C. **Diversity**: if one gene is producing protein adapted to +5...+30°C and other—to +10...+35°C, the organism may live under +5...+35°C

33.3 Diversity of life cycles

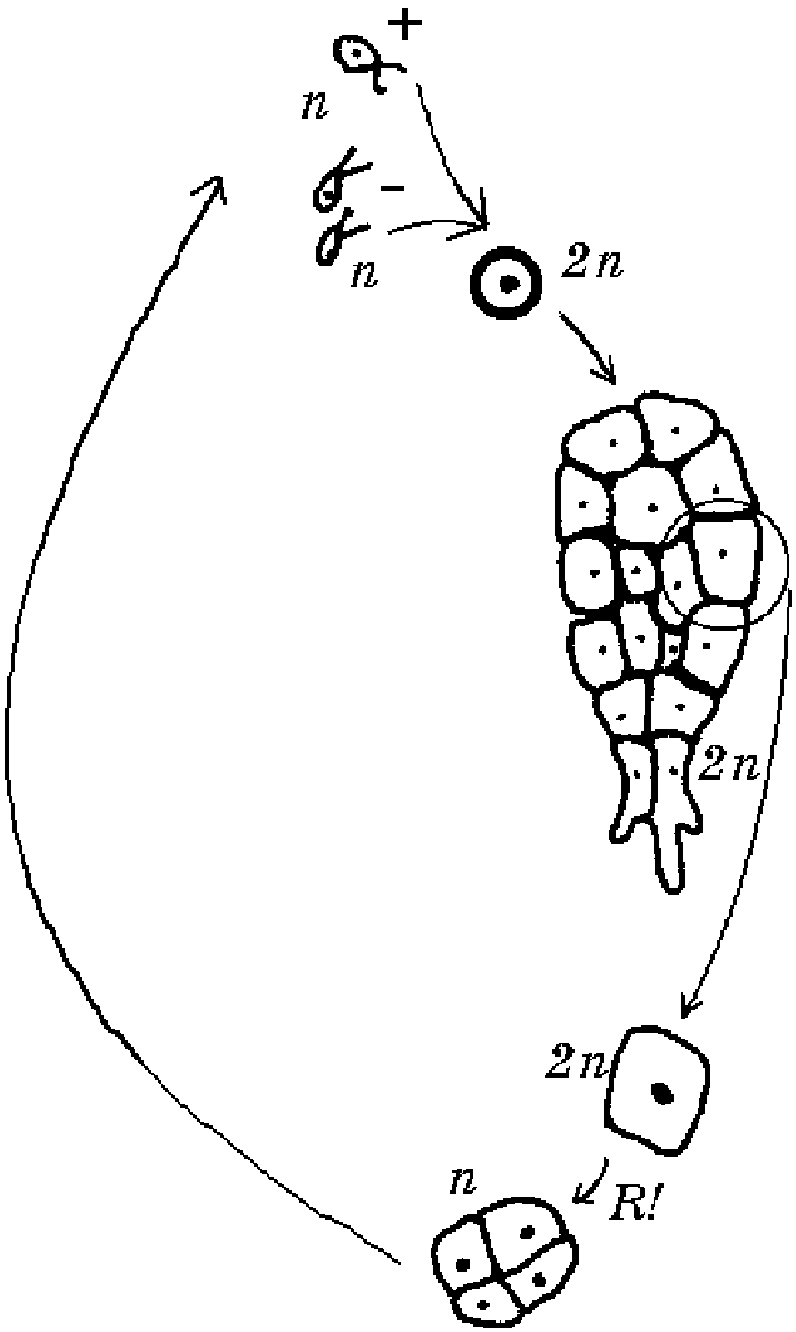
Zygotic life cycle: protists



Sporic life cycle: plants



Gametic life cycle: animals

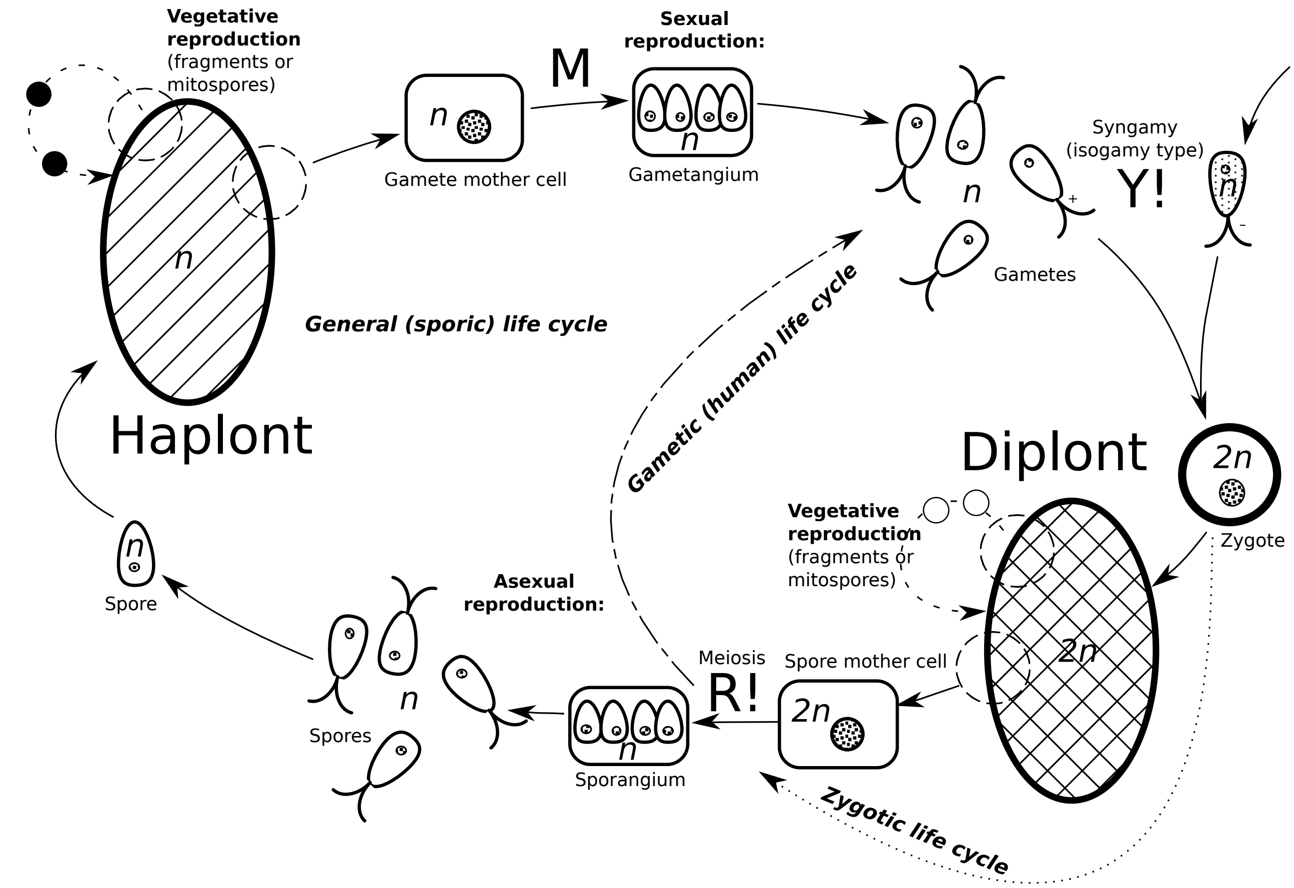


Life cycle math

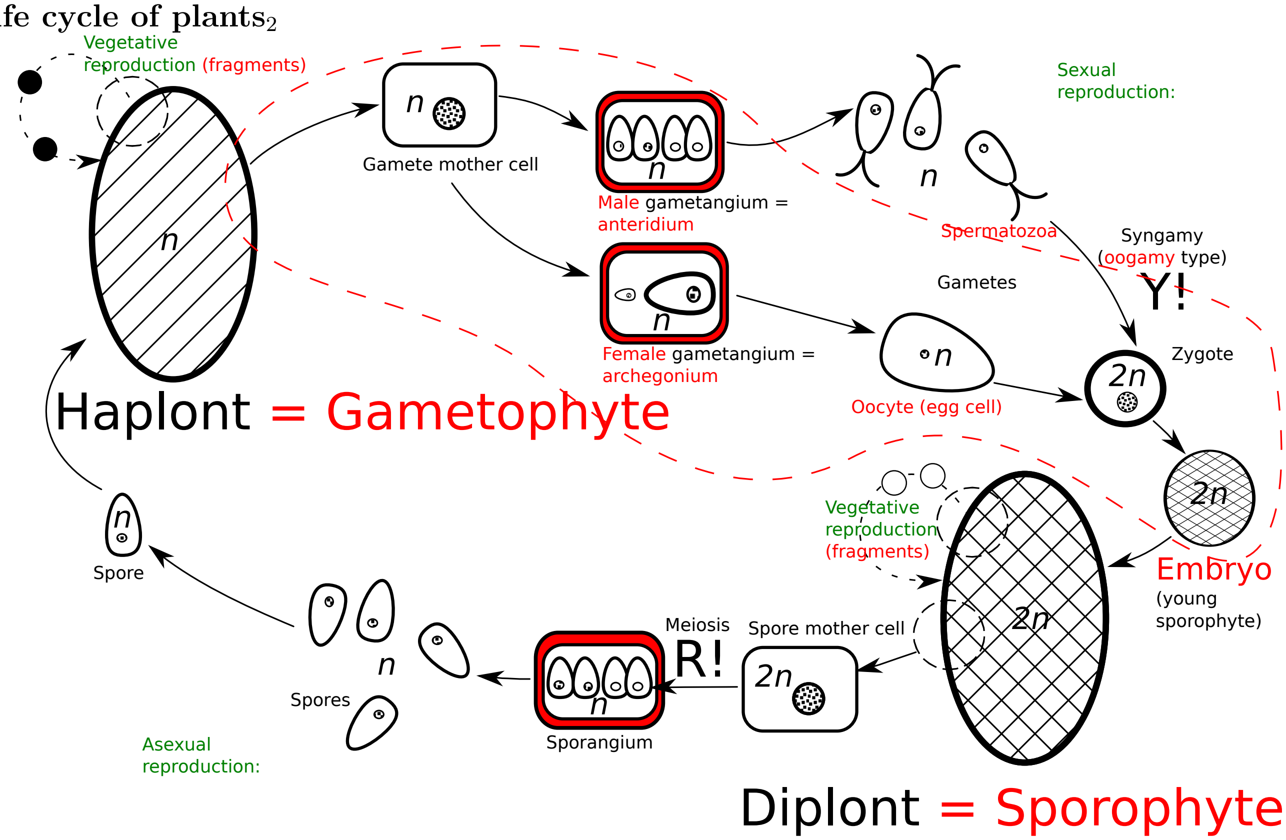
$$
\begin{tikzcd}
n_i \arrow[r] & \begin{array}{c}\text{Sexual reproduction}\\ \text{Syngamy (Y!)}\end{array} \arrow[r] \arrow[ddd, dashed, shift left=8, "1"] & 2n_1 \arrow[d] \\
\vdots \arrow[u] & & 2n_2 \arrow[d] \\
n_2 \arrow[u] & & \vdots \arrow[d] \\
n_1 \arrow[u] & \begin{array}{c}\text{Meiosis (R!)}\\ \text{Asexual reproduction}\end{array} \arrow[l] \arrow[uuu, dashed, shift left=8, "2"] & 2n_k \arrow[l]
\end{tikzcd}
$$

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`

34 Movie

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

Outline

35 Tissues

35.1 Origin of tissues

Origin of tissues and organs of plants: first steps

Why did plants go to the land? Which problems did they meet and how did they resolve them? What was the plant way of acquiring tissues comparing with animals?

35.2 Tissues basics

Definition of tissues and organs

- **Tissue** is a union of cells which have common origin, function, and similar morphology
- **Organ** is a union of different tissues which have common function(s) and origin

Simple and complex tissues

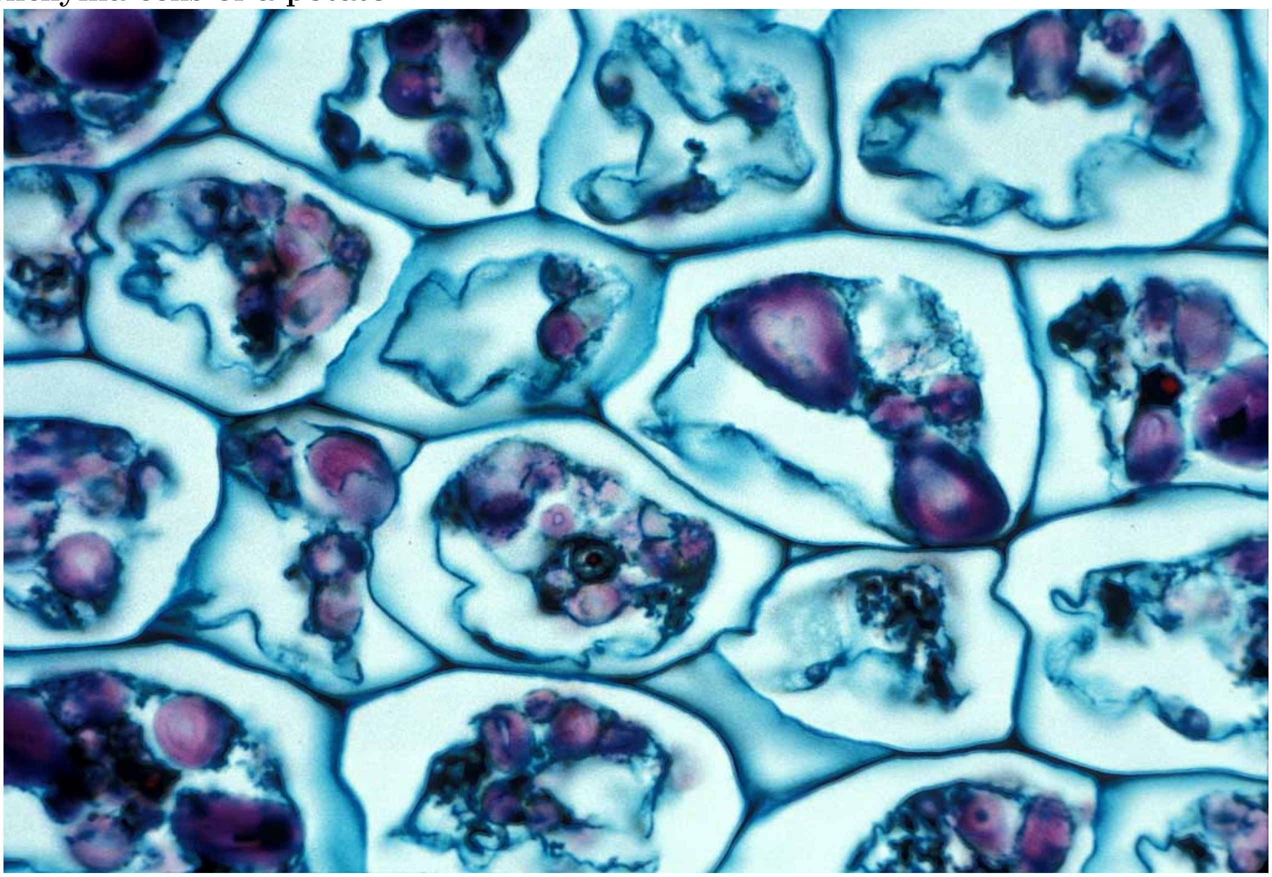
- **Simple tissues** have only one kind of cells
- **Complex tissues** have more than one cell type. This tissue type is unique for plants

35.3 First tissues: parenchyma and epidermis

Parenchyma (ground, main tissue)

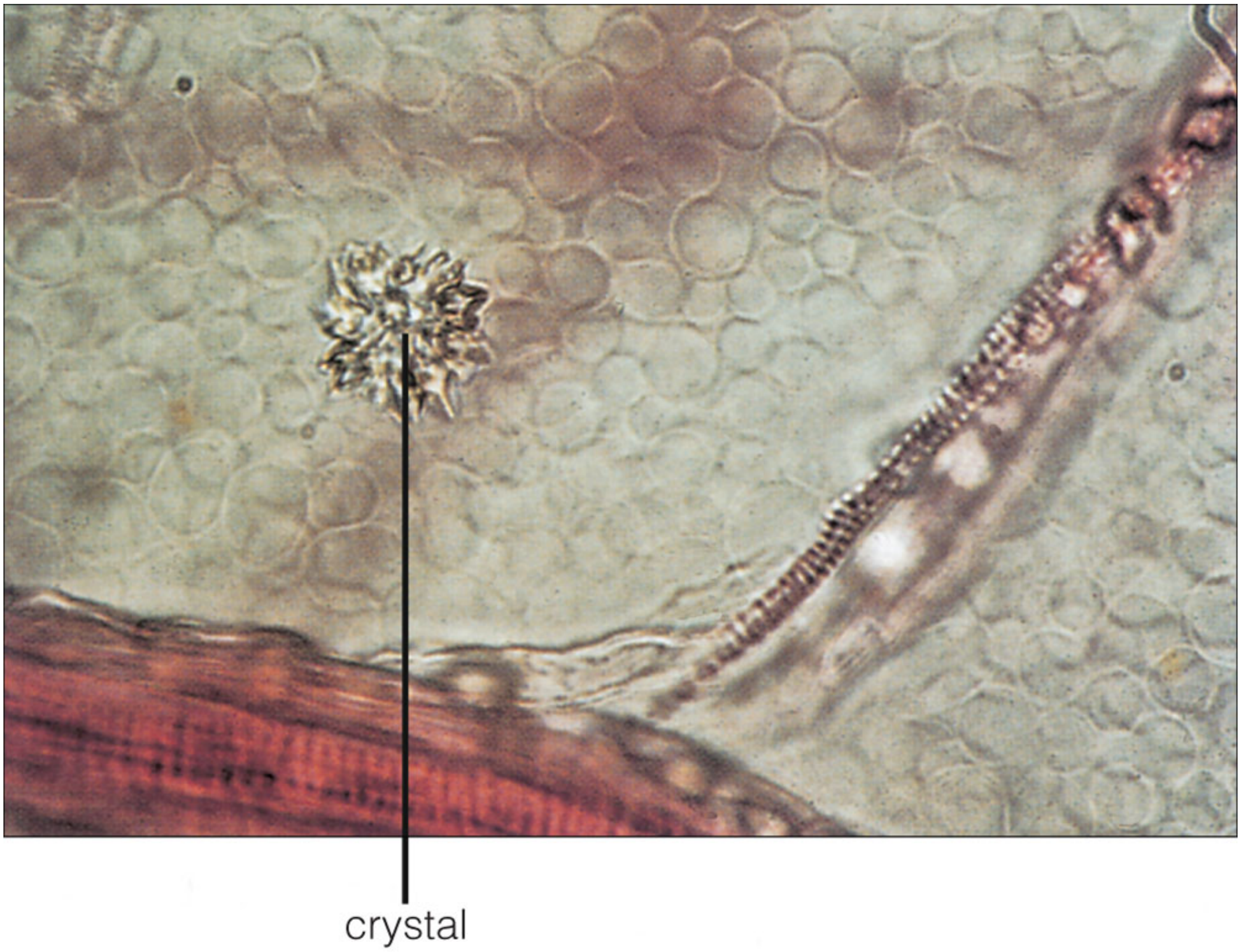
- Spherical or elongated cells
- Thin primary cell wall
- Sometimes, crystal inclusion bodies
- Main functions: photosynthesis and storage

Parenchyma cells of a potato



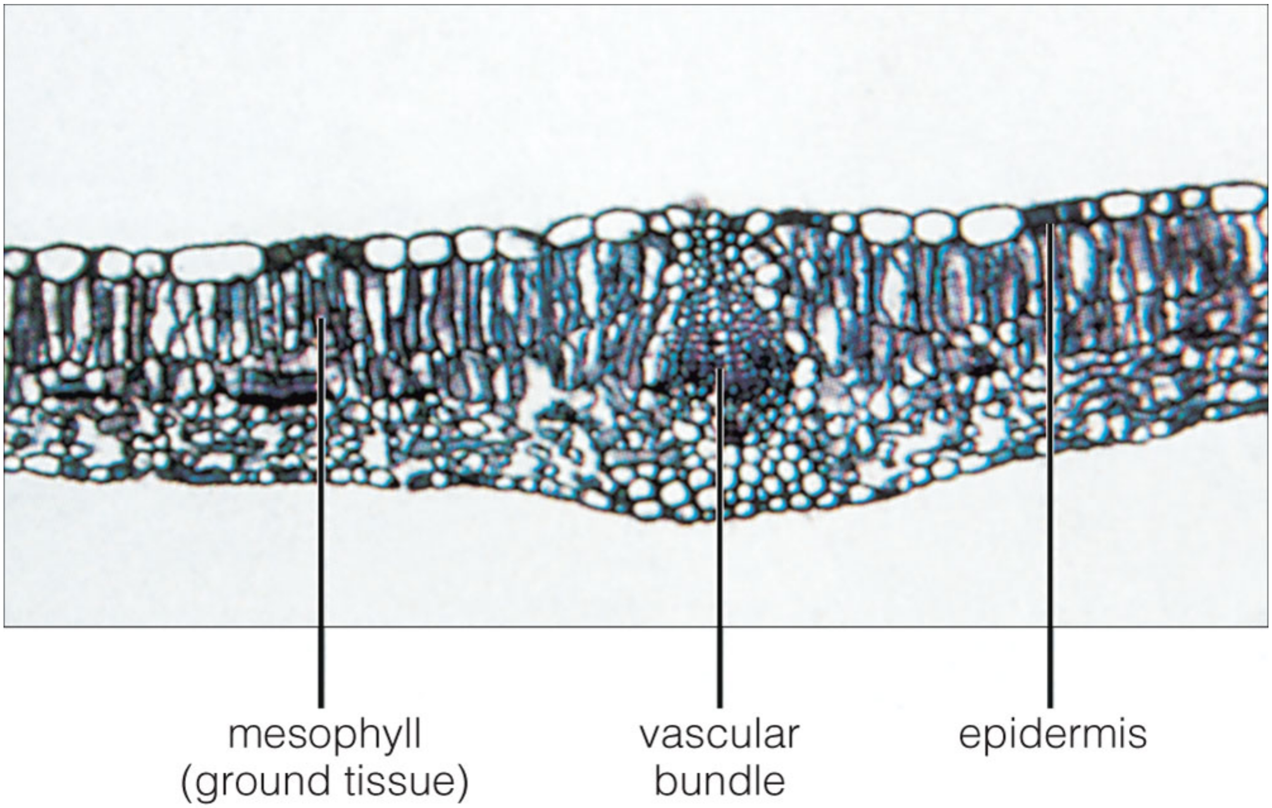
Parenchyma cells of a potato; the central cell shows obvious nucleus with starch stained purple (LM $\times 83$)

Parenchyma with crystals



Parenchyma cells often include crystals (e.g., of calcium oxalate)

Photosynthetic parenchyma



Photosynthetic parenchyma (mesophyll) in lilac (*Syringa vulgaris*) leaf

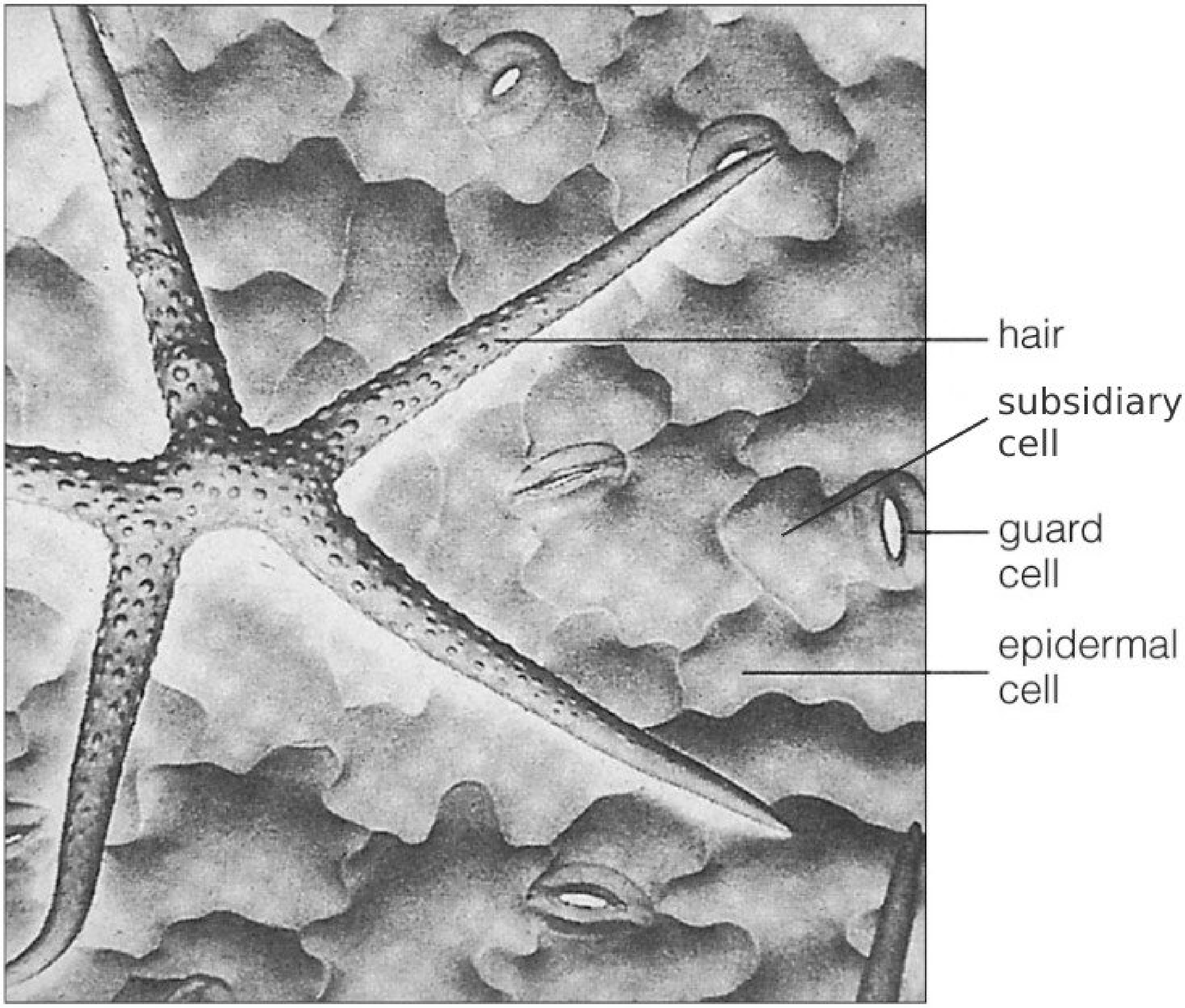
Epidermis: the complex tissue

- Complex tissue of different cell types:

  A. Epidermal cells
  B. Stomata cells:
     - Guard cells
     - Subsidiary cells
  C. Trichomes

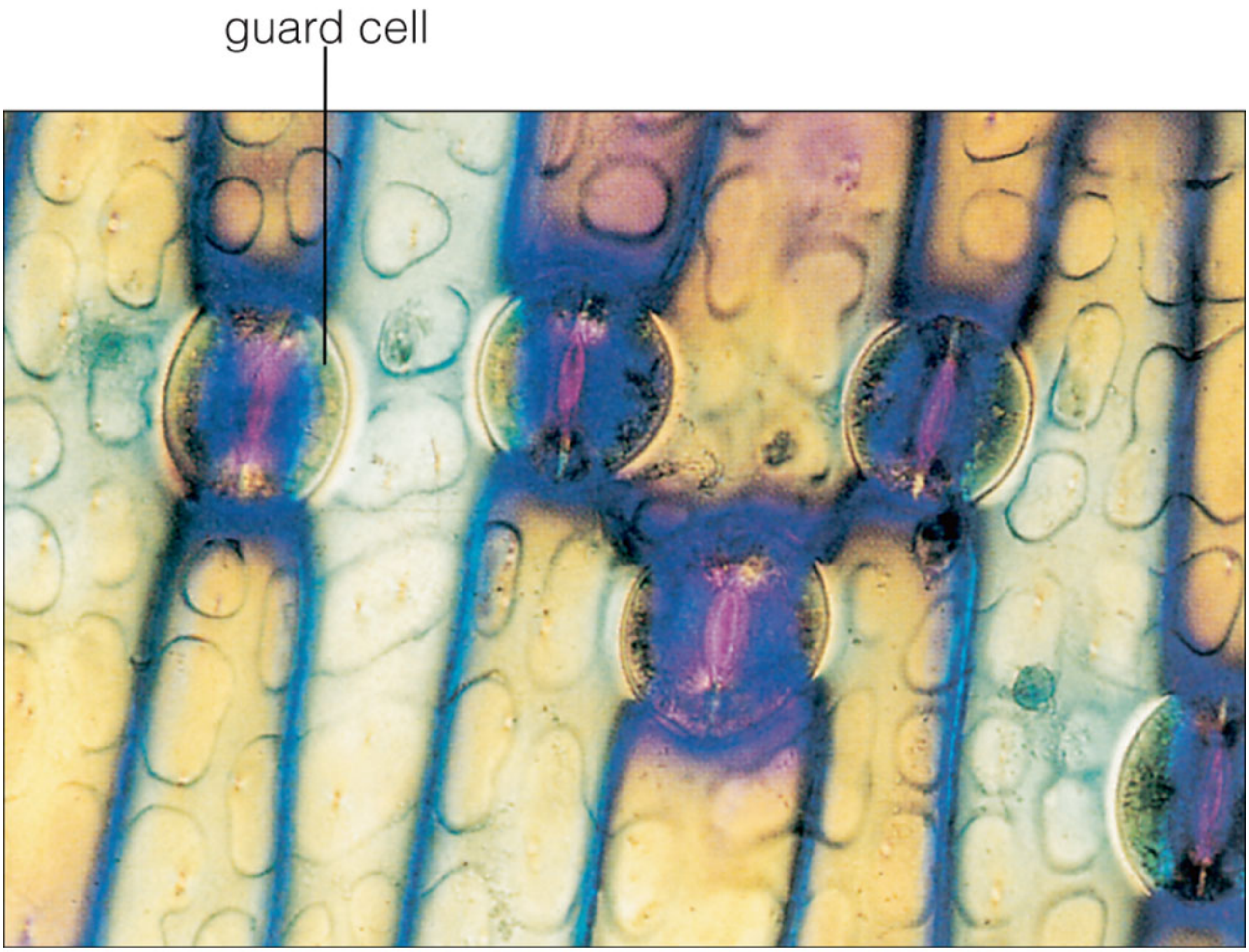
- Shapes and chemical compounds vary
- Main functions: gas exchange, transripration, defense

Epidermal cells



Three kinds of Shepard's purse (*Capsella bursa-pastoris*) epidermal cells

Stomata



Stomata with guard cells and pores (*Iris* sp.)

More about plants$_2$ classification

- Mosses (Bryophyta)
- Ferns and allies (Pteridophyta)
- Seed plants (Spermatophyta)
  - Conifers (Pinopsida)
  - Some other classes of seed plants
  - Angiosperms (Magnoliopsida)
    - Monocots (Liliidae)
    - Other subclasses of angiosperms (together: "dicots")

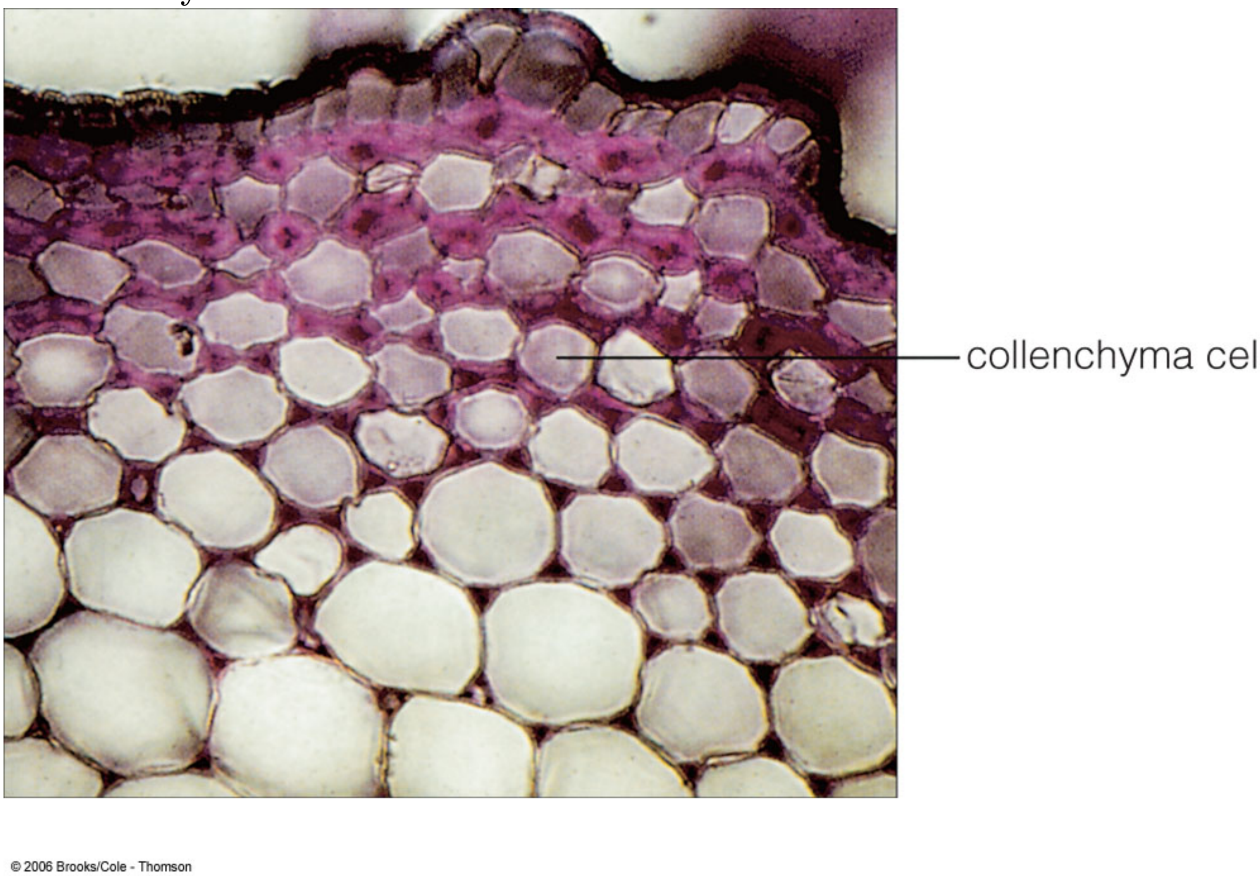
35.4 Step two: skeleton. Supportive tissues

Collenchyma: living supportive tissue

- Elongated cells

- Thick primary cell wall (pectins + cellulose)
- Main functions: mechanical support of young stems and leaves

Angled collenchyma

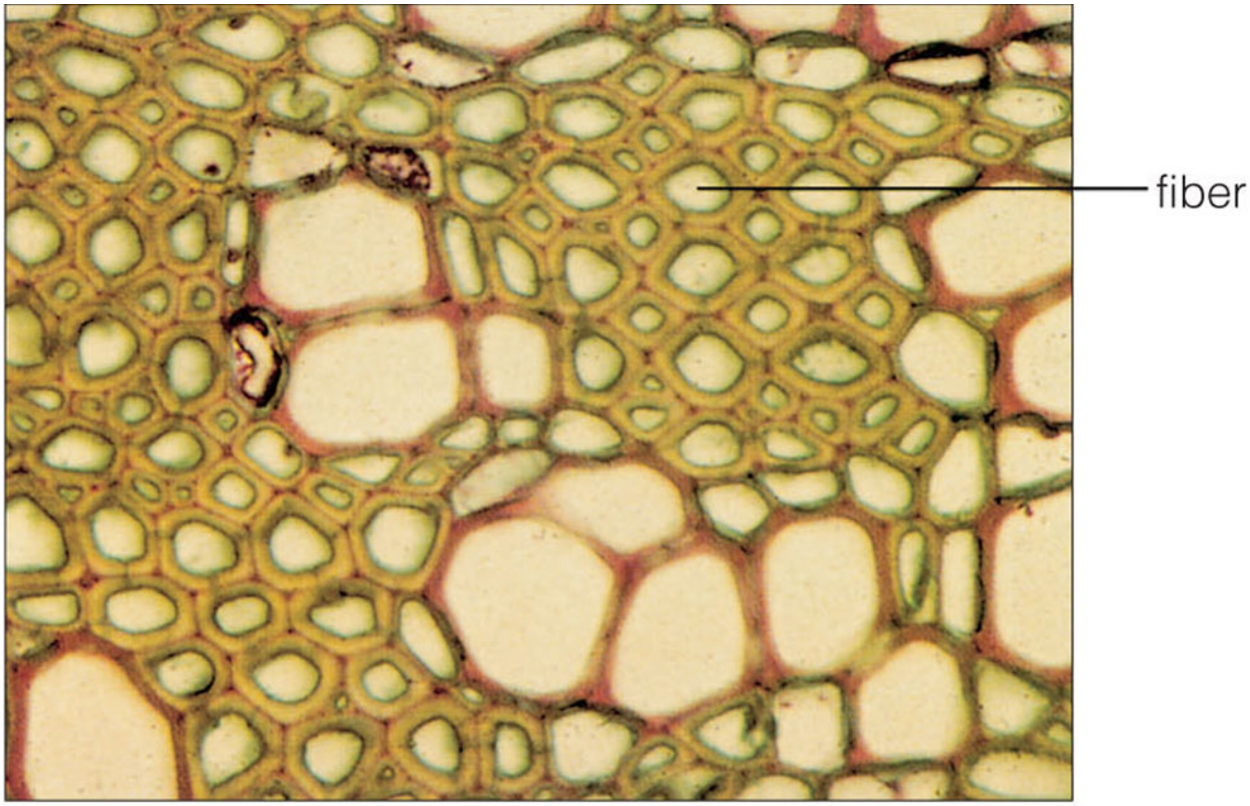


Collenchyma cells of marigold (*Calendula officinalis*)

Sclerenchyma: dead supportive tissue

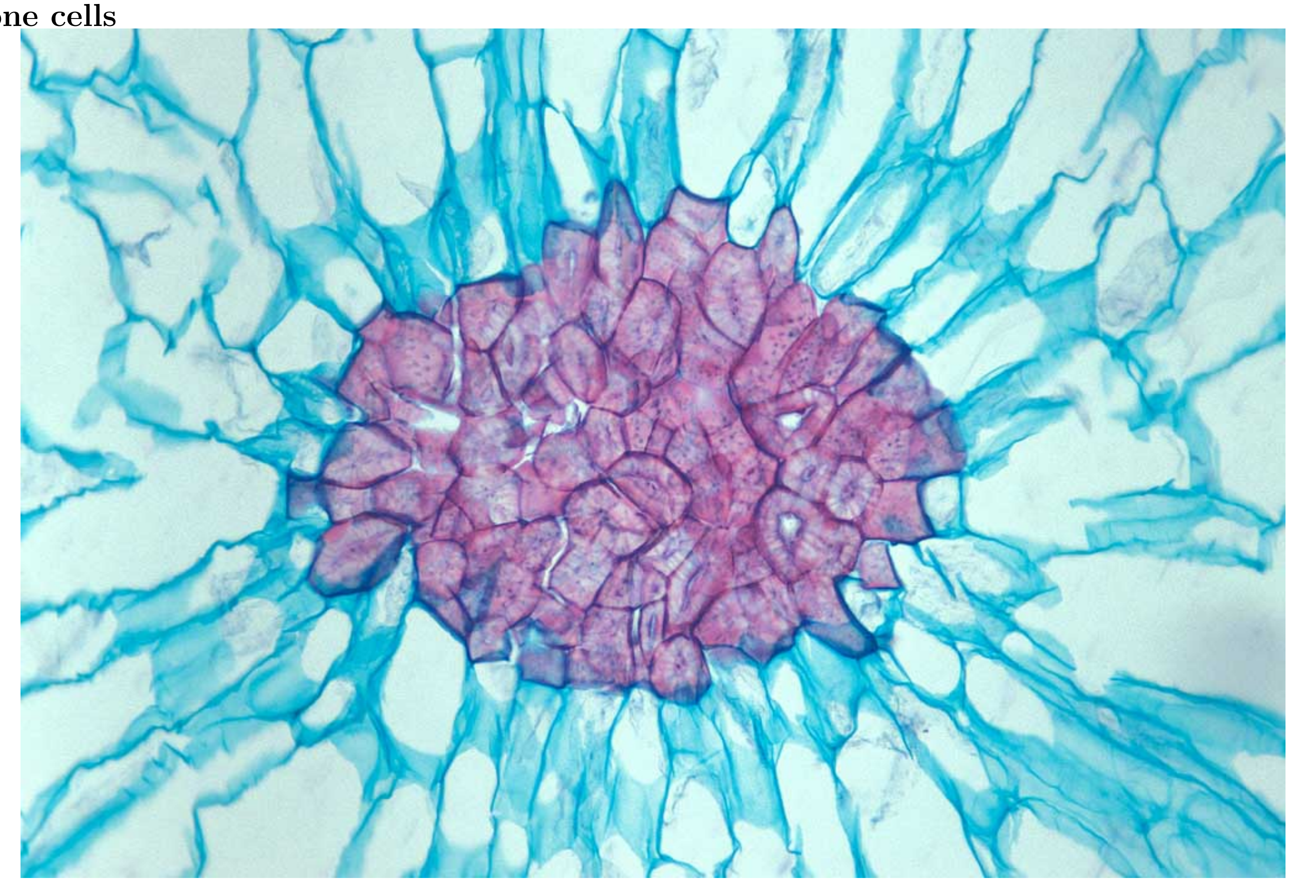
- Long cells (sclerenchyma fibers) or short crystal-like cells (sclereids)
- Dead cells with thick secondary cell wall, rich of lignin
- Supports weight of older plant organs, makes fruits non-edible before they become rip, makes stems firm

Sclerenchyma fibers



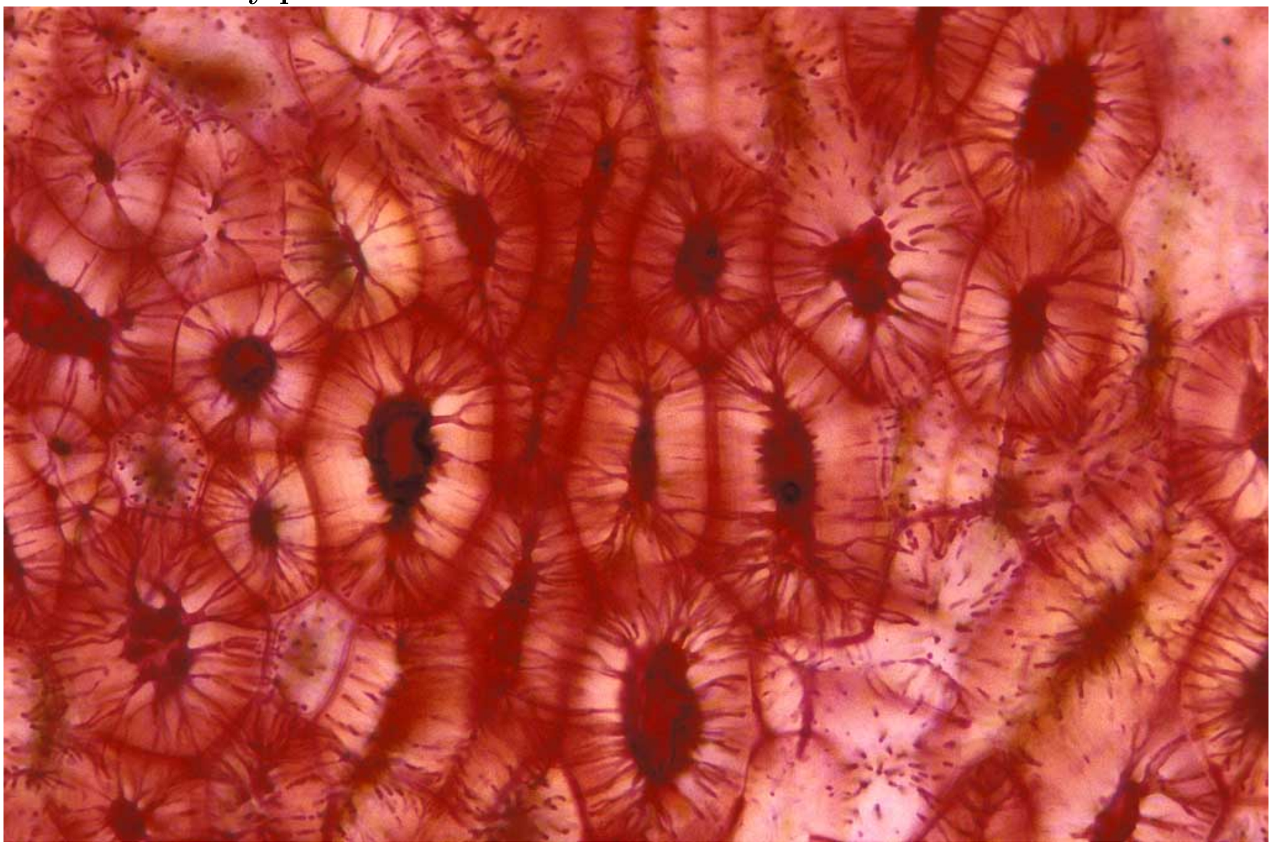
Cross-section of sclerenchyma fibers in geranium (*Pelargonium* sp.)

Stone cells



Stone cells (kind of sclereids) in pear fruit (*Pyrus communis*)

Sclereids from cherry pit



Sclereids from cherry (*Prunus* sp.) pit (LM ×400)

35.5 Step three: construction sites. Meristems

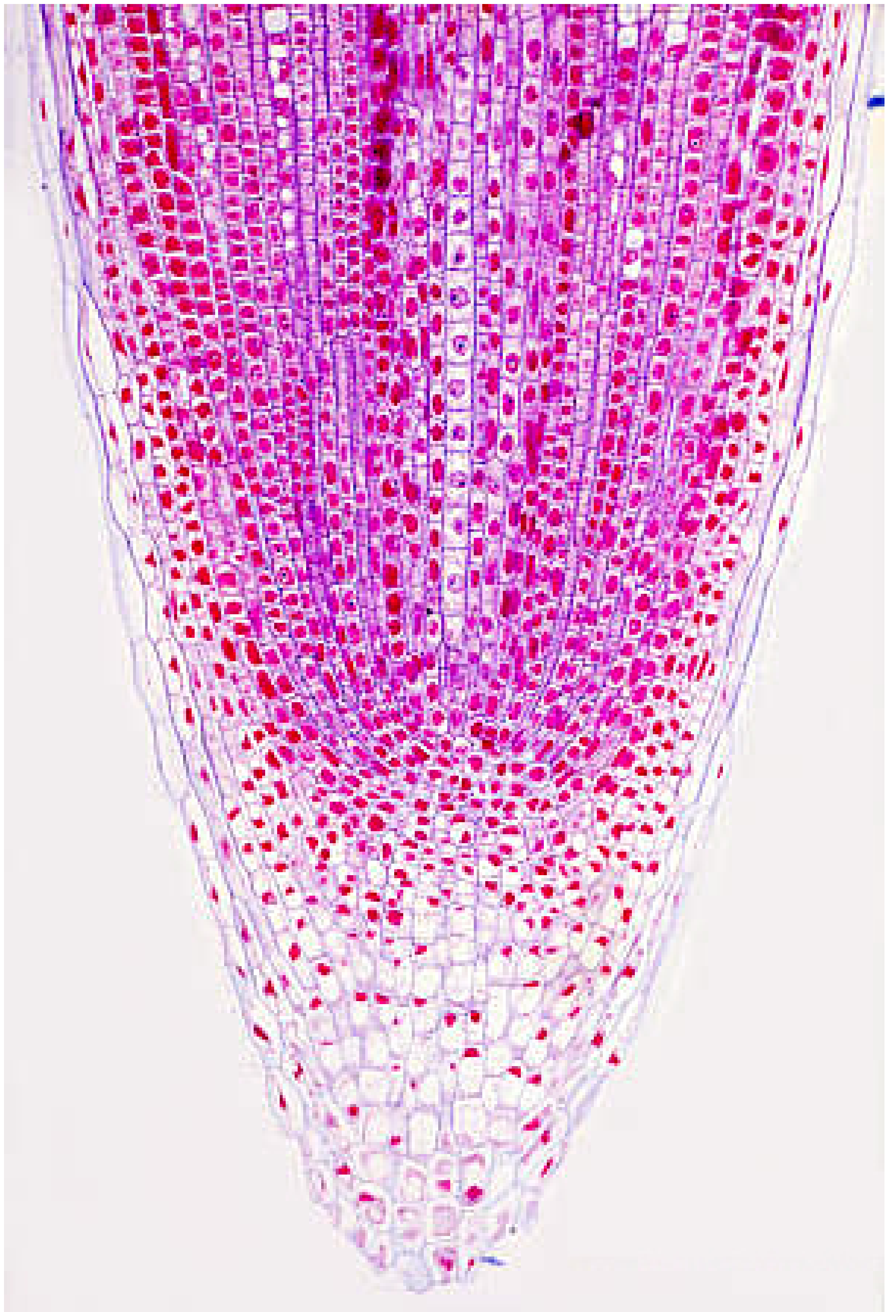
Meristems: apical

- Centers of plant development
- Locate on the very ends of roots (RAM) and shoots (SAM)
- Produce intermediate primary meristems which form all primary tissues

SAM

Coleus sp. stem apical meristem (LM ×100); primordia (embryonic leaves) are visible.

RAM



Corn (*Zea mays*) root apical meristem (© D. Webb)

Lateral meristem: cambium

- Originates from procambium which in turn originates from apical meristems
- Usually arises between two vascular tissues
- Main function: thickening. Produces secondary vascular tissues

Primary and secondary tissues

- Primary tissues originate from stem or root apex through primary meristems
- Secondary tissues originate from lateral meristems

Additional meristems

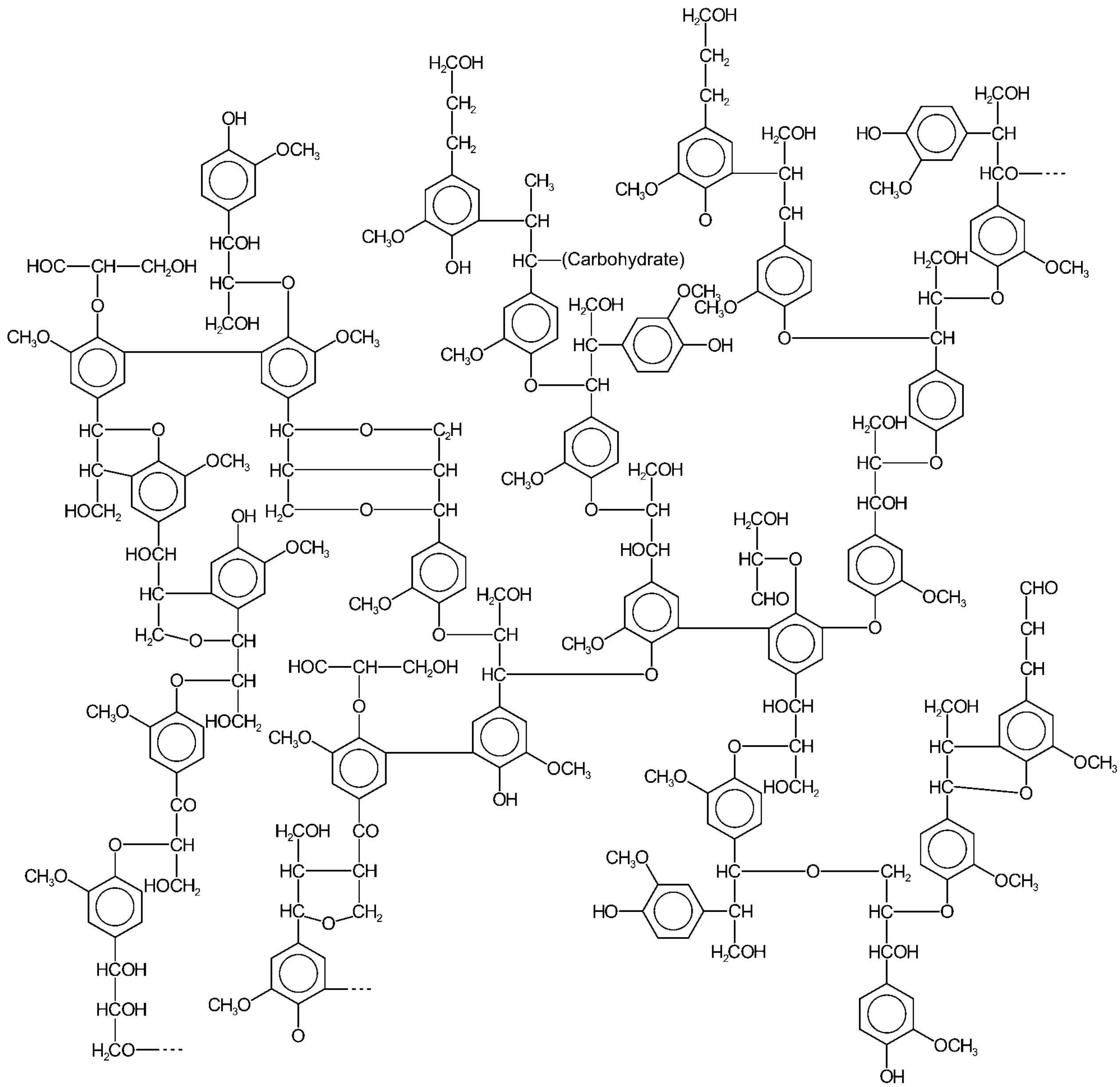
- **Intercalary** meristems: locate in stems, regulates stem elongation
- **Marginal** meristems are leaf-specific, they regulate leaf shape
- **Repair** meristems help to cure wounds, they form buds and roots in unusual places

35.6 Origin of tissues: the summary

Origin of tissues and organs of plants: first steps

- Plants were pushed on land for many reasons, including competition
- First challenge: drying. Response: **epidermis** and **parenchyma**.
- Second challenge: new level of competition. Response: growing up!
- Problem: big weight. Response: **collenchyma**.
- Competition grows, plants growing even higher. Weight grows. They also need to get rid of turgor dependency. Response: use lignin not only for epidermis surface (cuticle) but also for secondary cell walls—**sclerenchyma**.
- Competition grows again, plants need to grow faster. Solution: **meristems**.
- Size of plant is too big for plasmodesmata transportations. Solution: vascular tissues, **xylem** and **phloem**.

Lignin



Phenolic and other "plastic" compounds (e.g., lignin) were initially developed for spore distribution with a wind, then used in cuticle, then in the secondary cell walls.

35.7 Step four: pipes. Vascular tissues

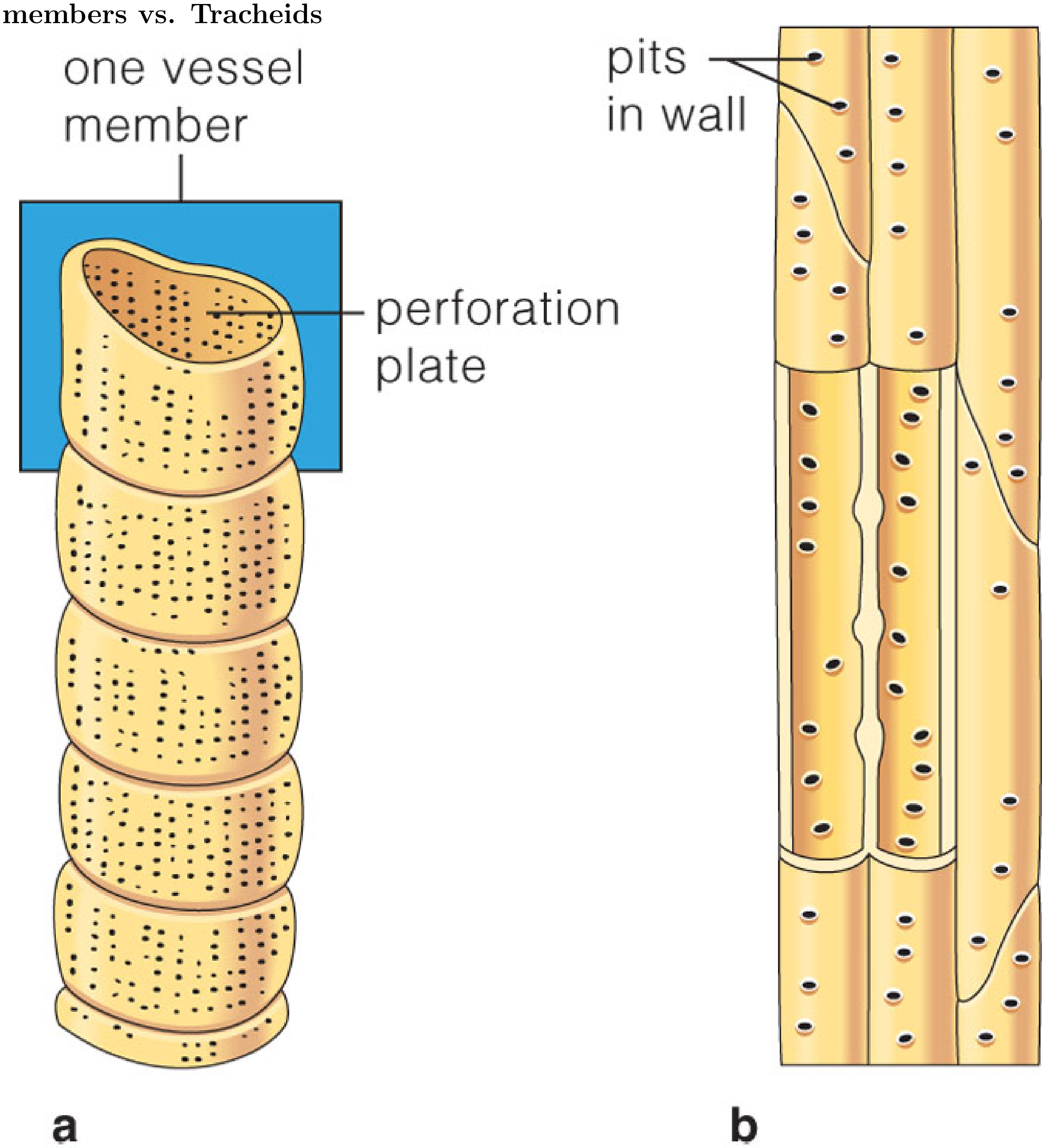
35.7.1 Xylem

Vascular tissues: Xylem

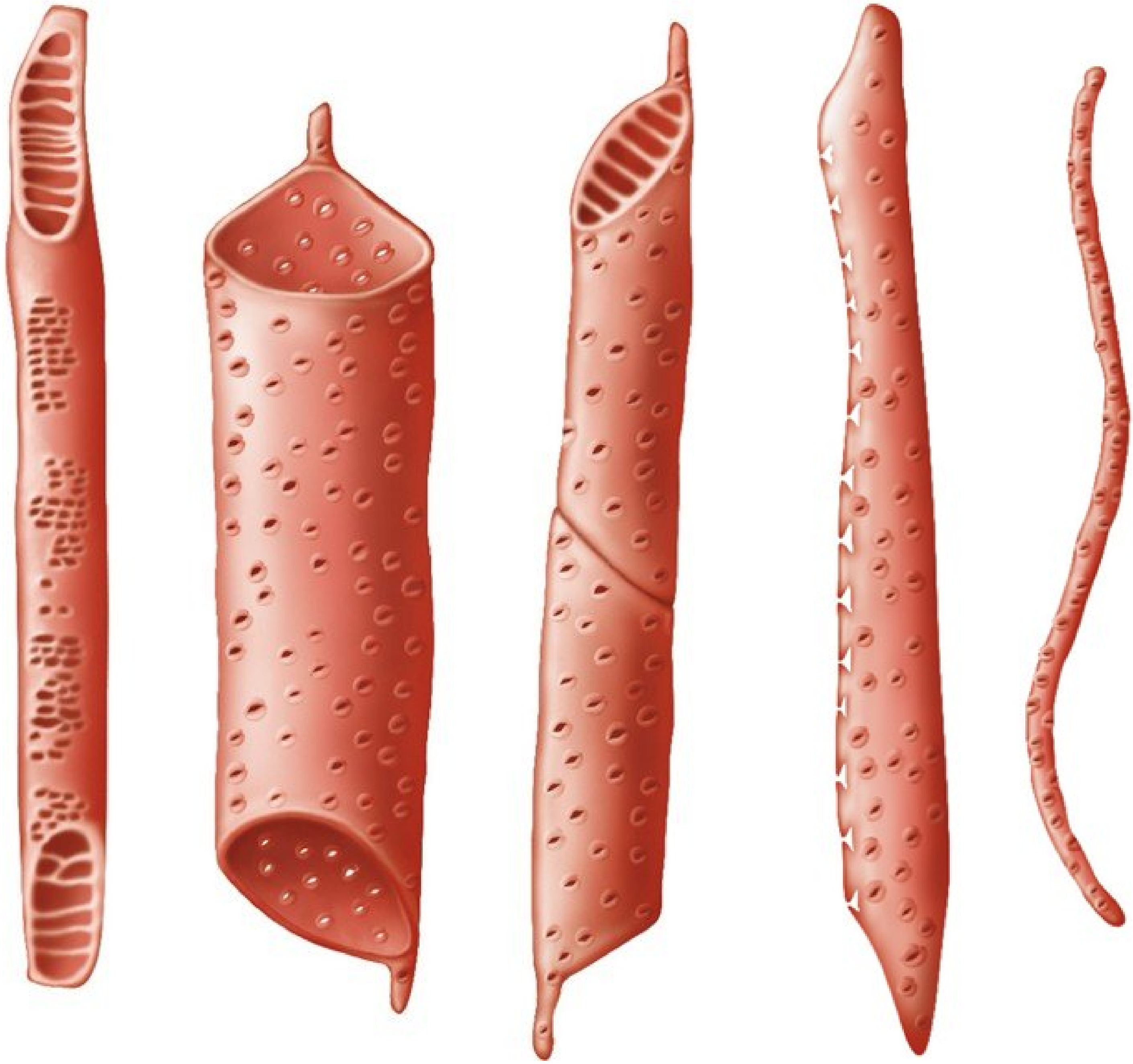
- Occurs in vascular bundles or vascular cylinder
- Types of cells: **tracheary elements** (tracheids and vessel members), **fibers**, and **parenchyma**
- Tracheids have pits; vessel members have perforations; all of them are dead cells
- Gymnosperms have only tracheids; flowering plants have tracheids + vessel elements together
- In flowering plants, primary xylem has mostly tracheids and vessels with scalariform perforations; secondary xylem has mostly vessels with open perforations

- Xylem elements (except parenchyma) are rich of lignin and are main components of wood
- Main functions: water transport and mechanical support

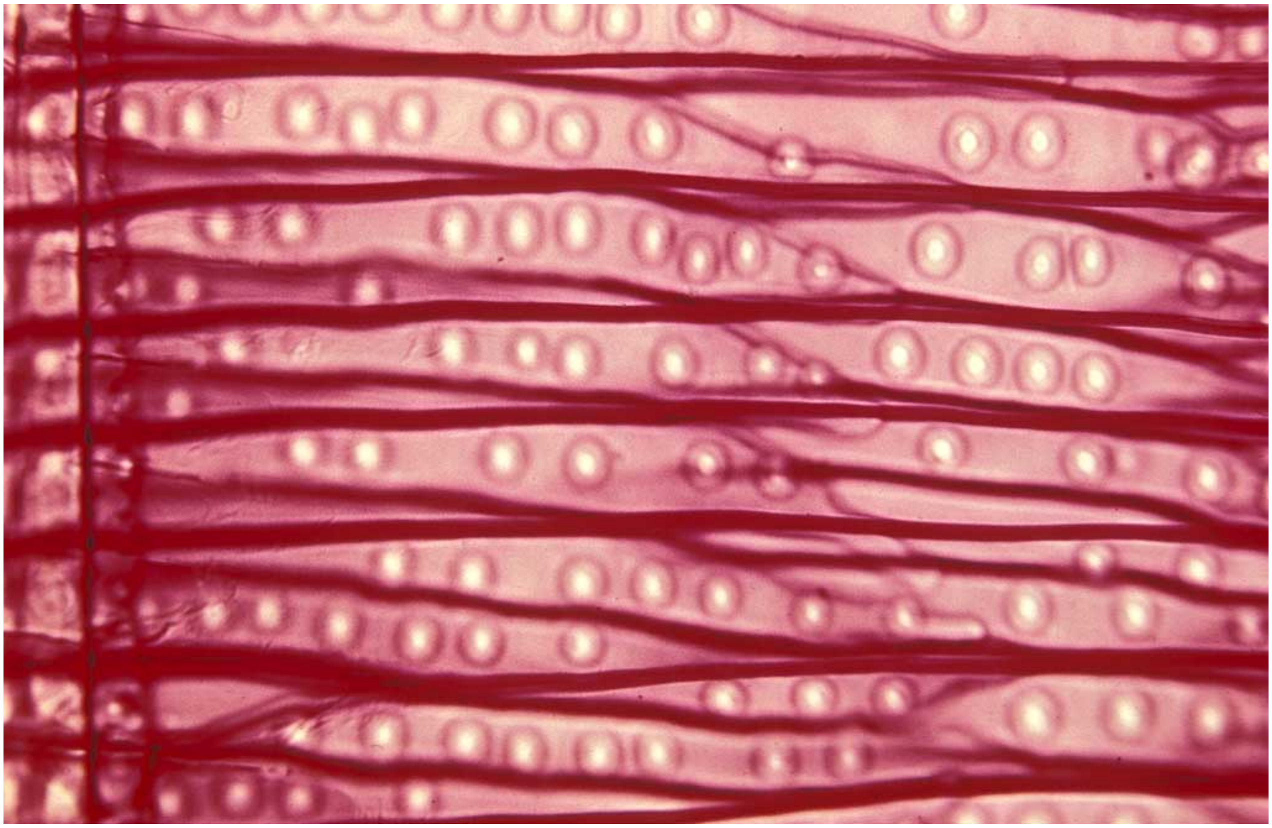
Vessel members vs. Tracheids



Vessel members vs. Tracheids

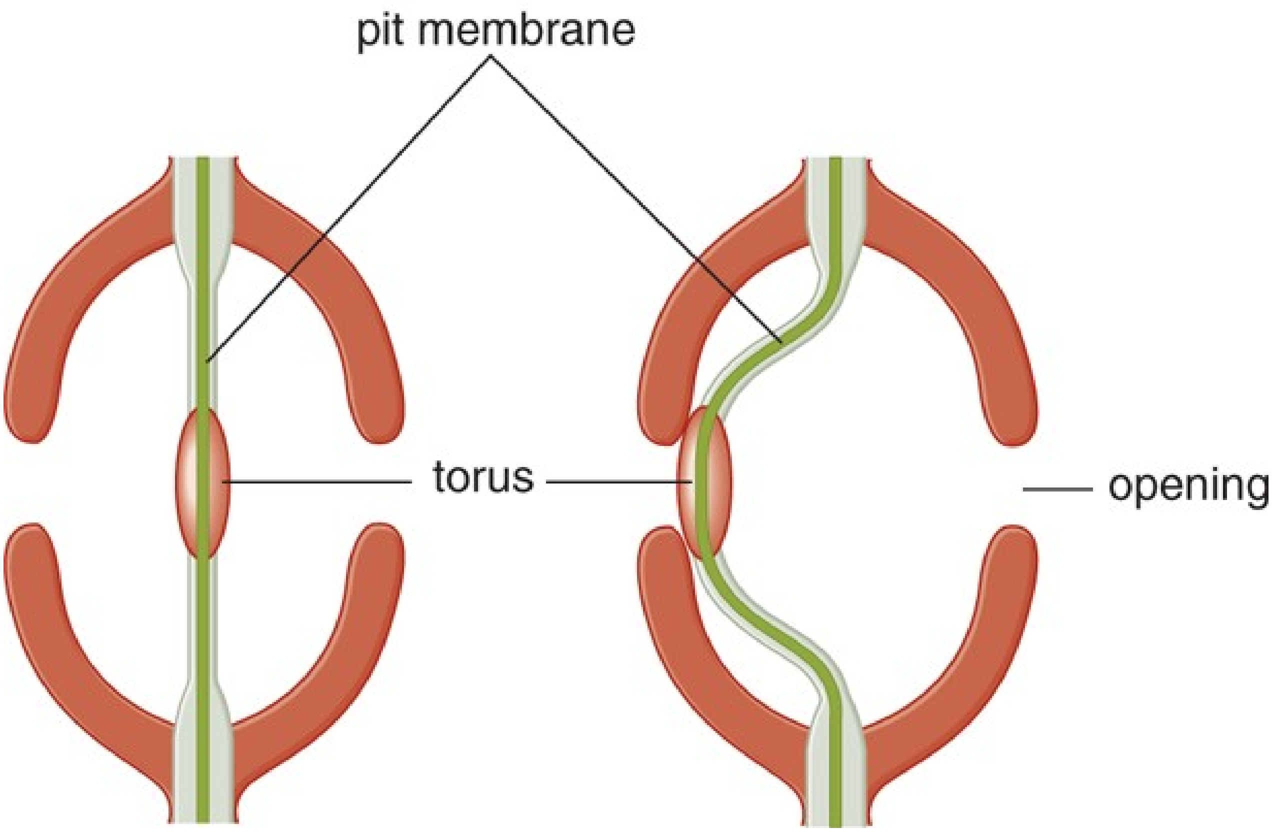


Tracheids



Pine (*Pinus* sp.) tracheids with pits

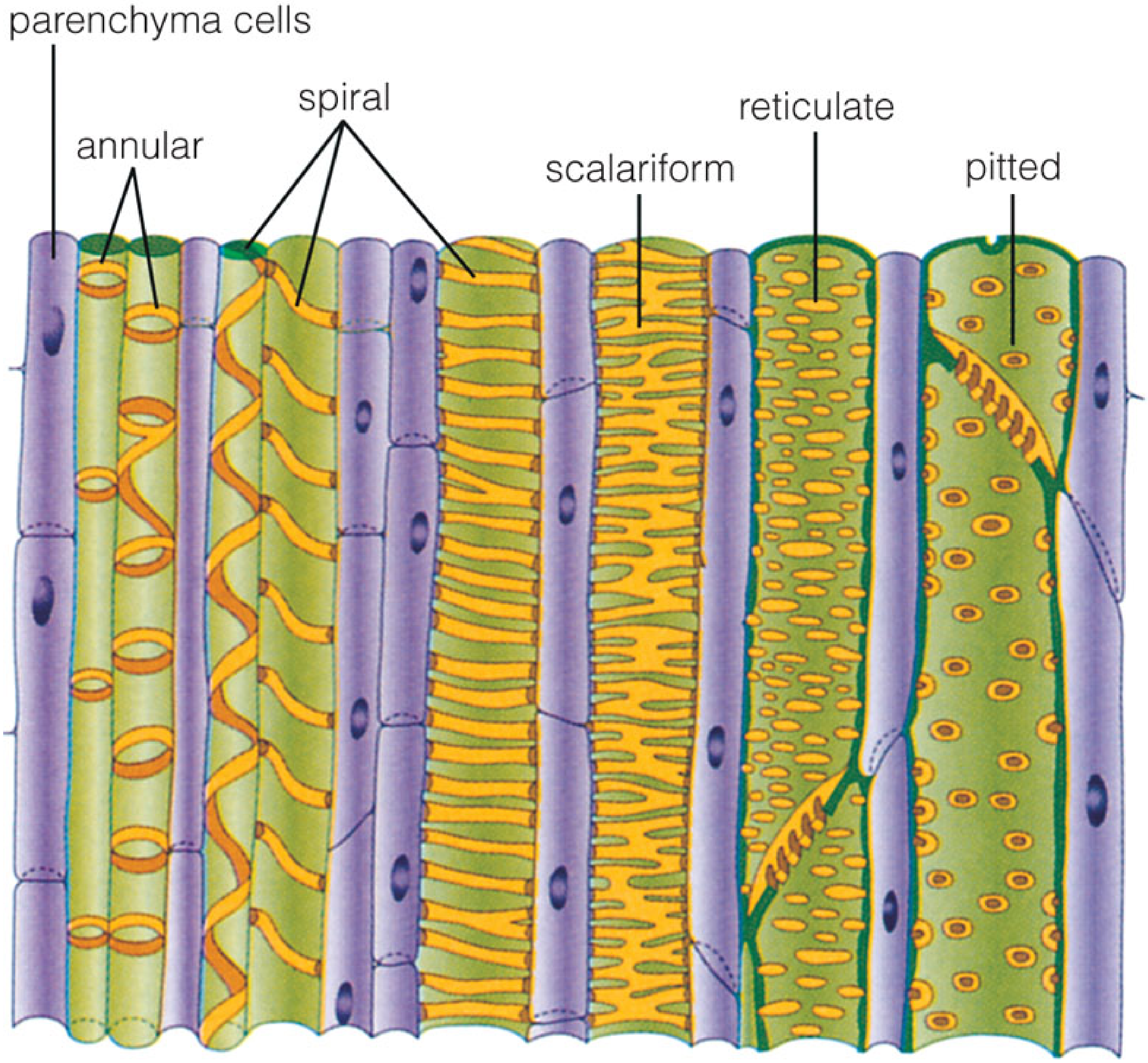
Pit is NOT a direct connection



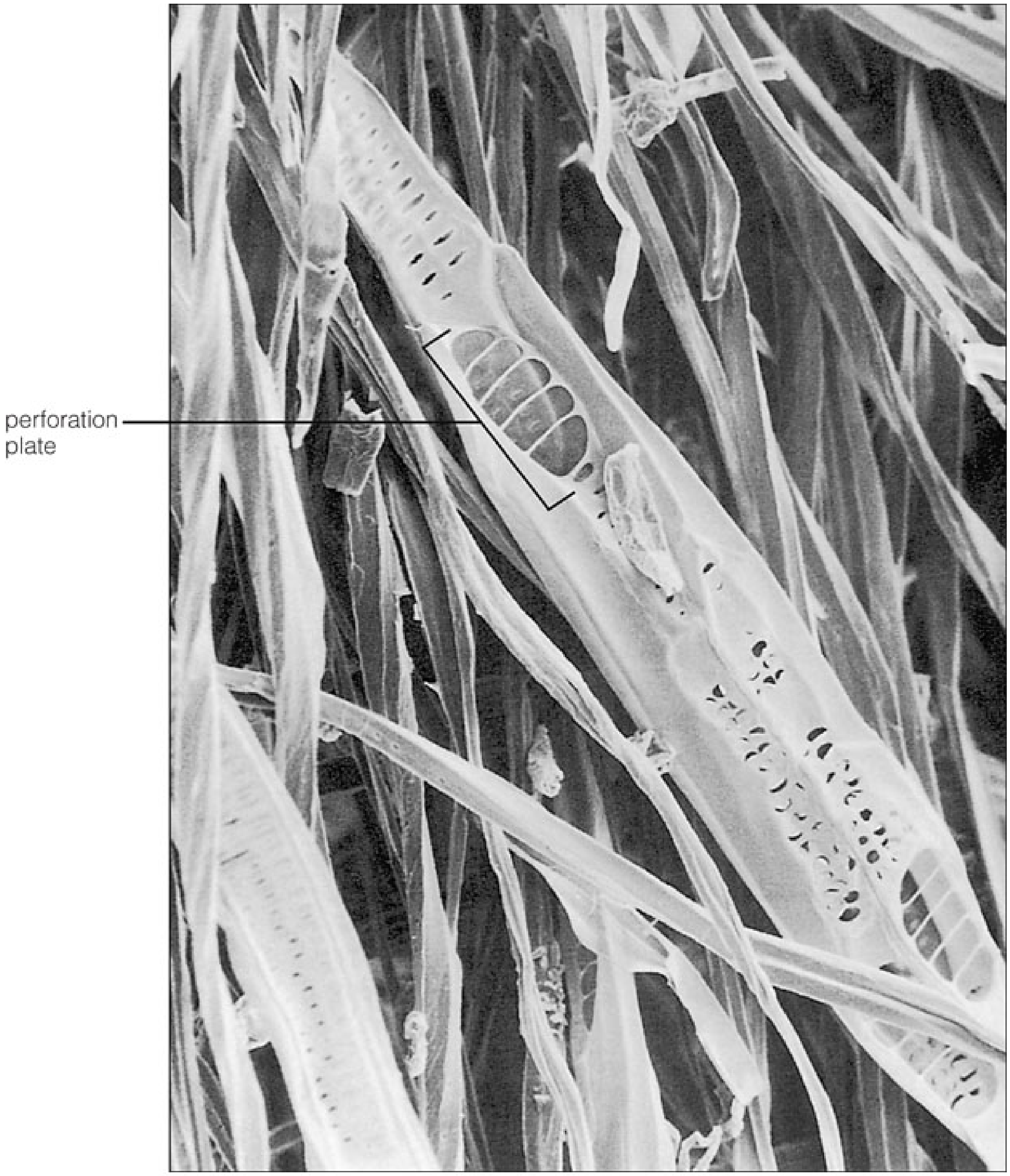
Vessels


Ash (*Fraxinus americana*) secondary xylem with vessels (LM ×26)

Perforations



Scalariform perforations: direct connections

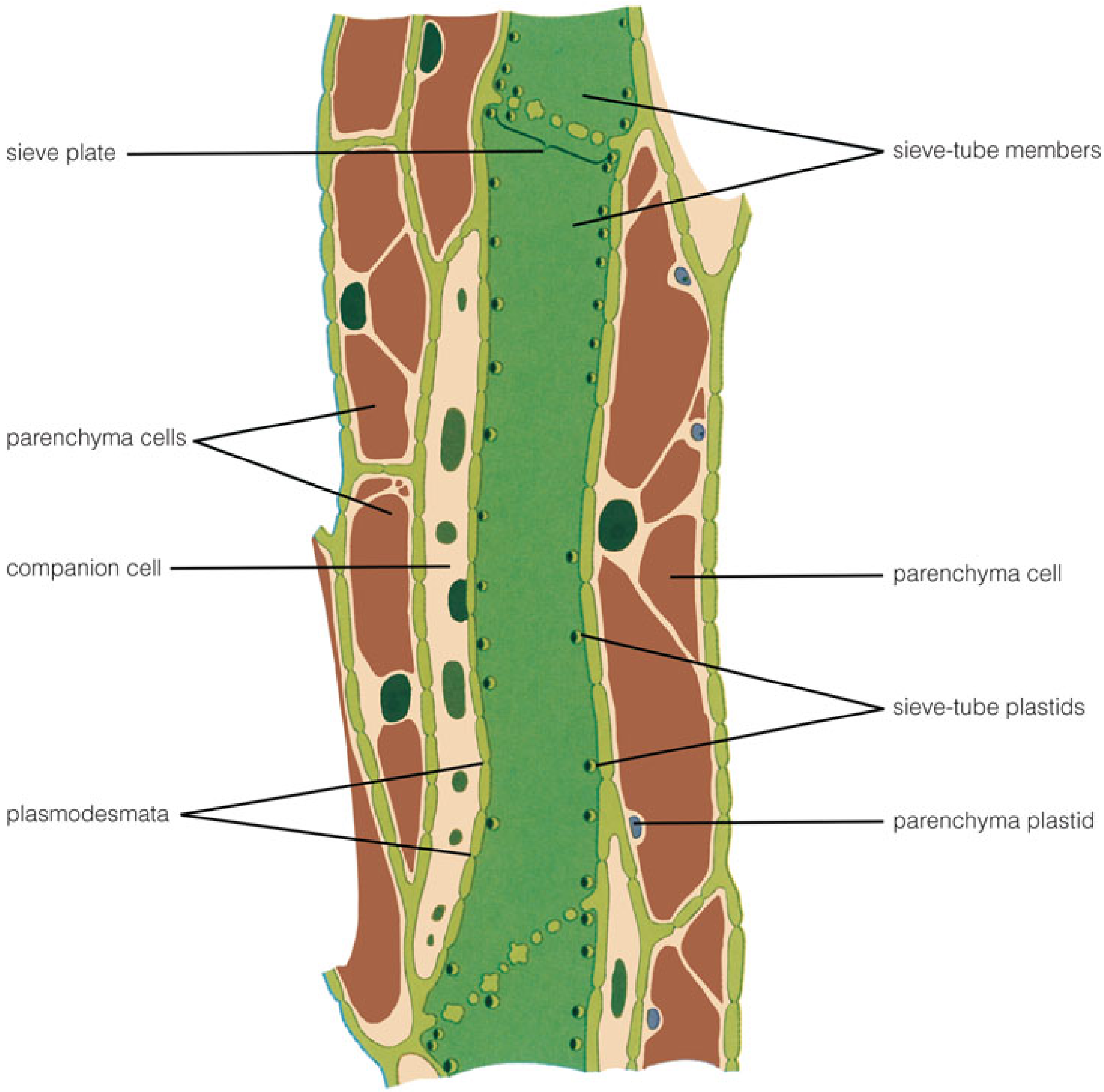


35.7.2 Phloem

Phloem

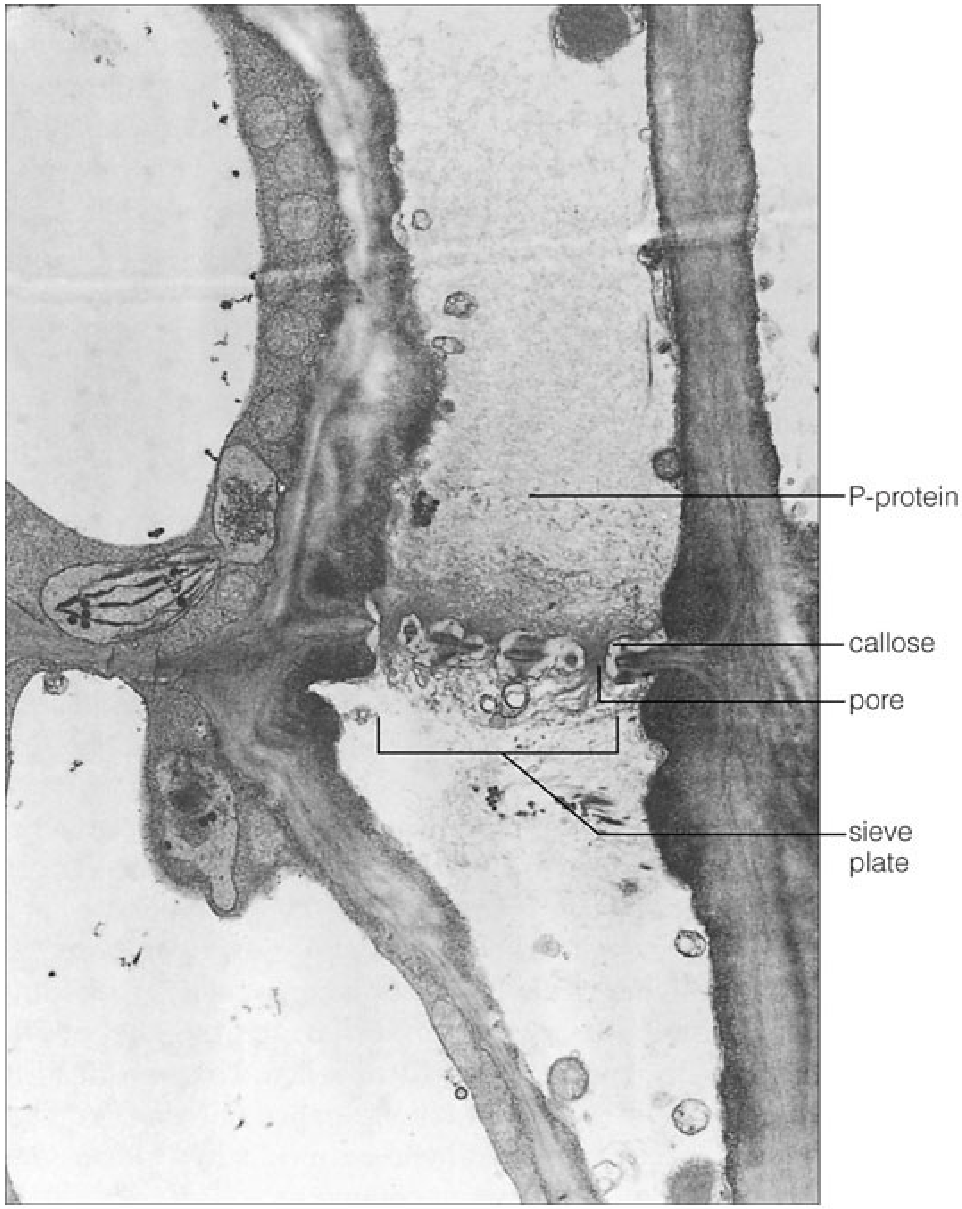
- Usually occurs adjacent to a xylem
- Types of cells: **sieve tube cells**, **companion cells**, **fibers** and **parenchyma**
- Sieve tube cells have plastids and perforation (sieve) plates between cells but no nuclei, companion cells have nuclei
- However, in gymnosperms there are *no* companion cells and sieve tube cells *have* nuclei
- Secondary phloem usually has more fibers than primary phloem
- Main functions: sugar transport and mechanical support

Phloem cell types



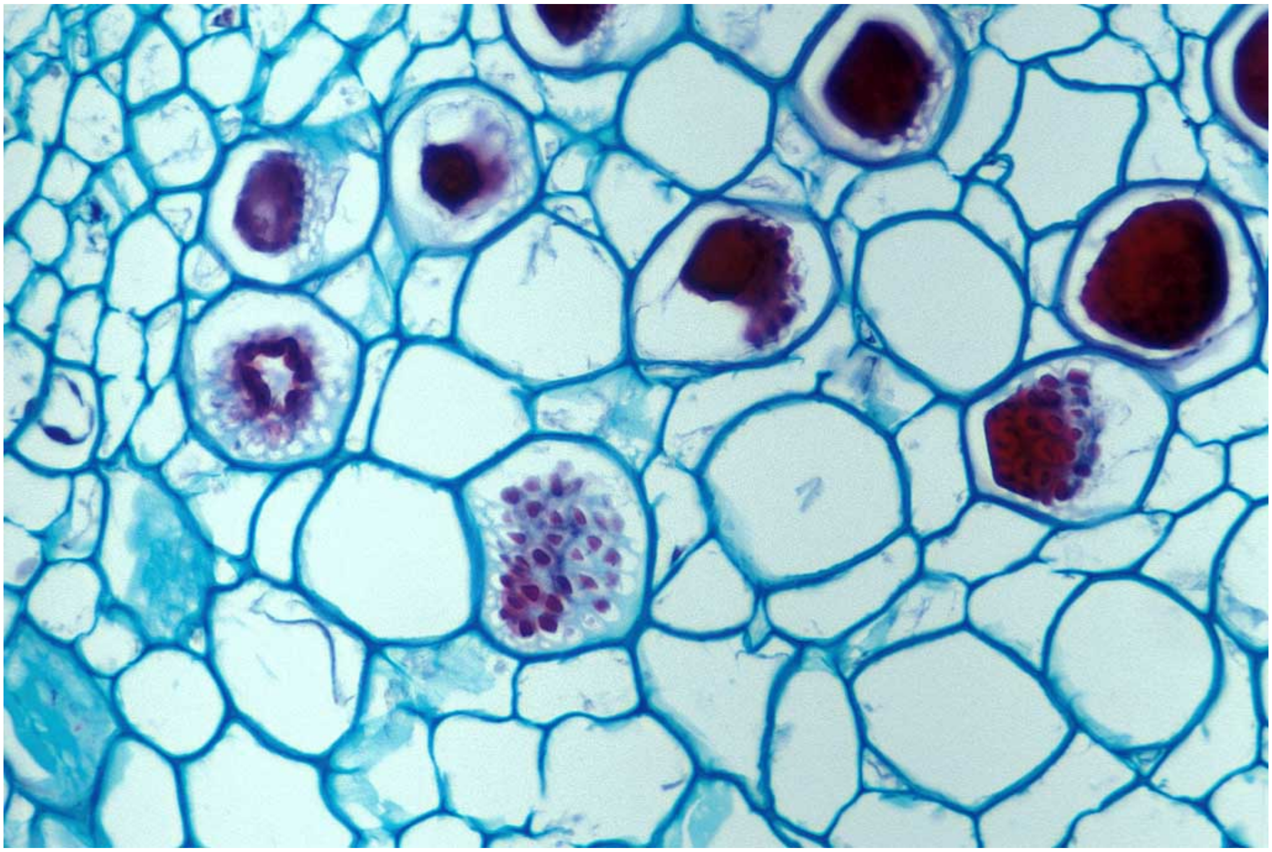
Sieve tubes and phloem parenchyma

Perforation (sieve) plate

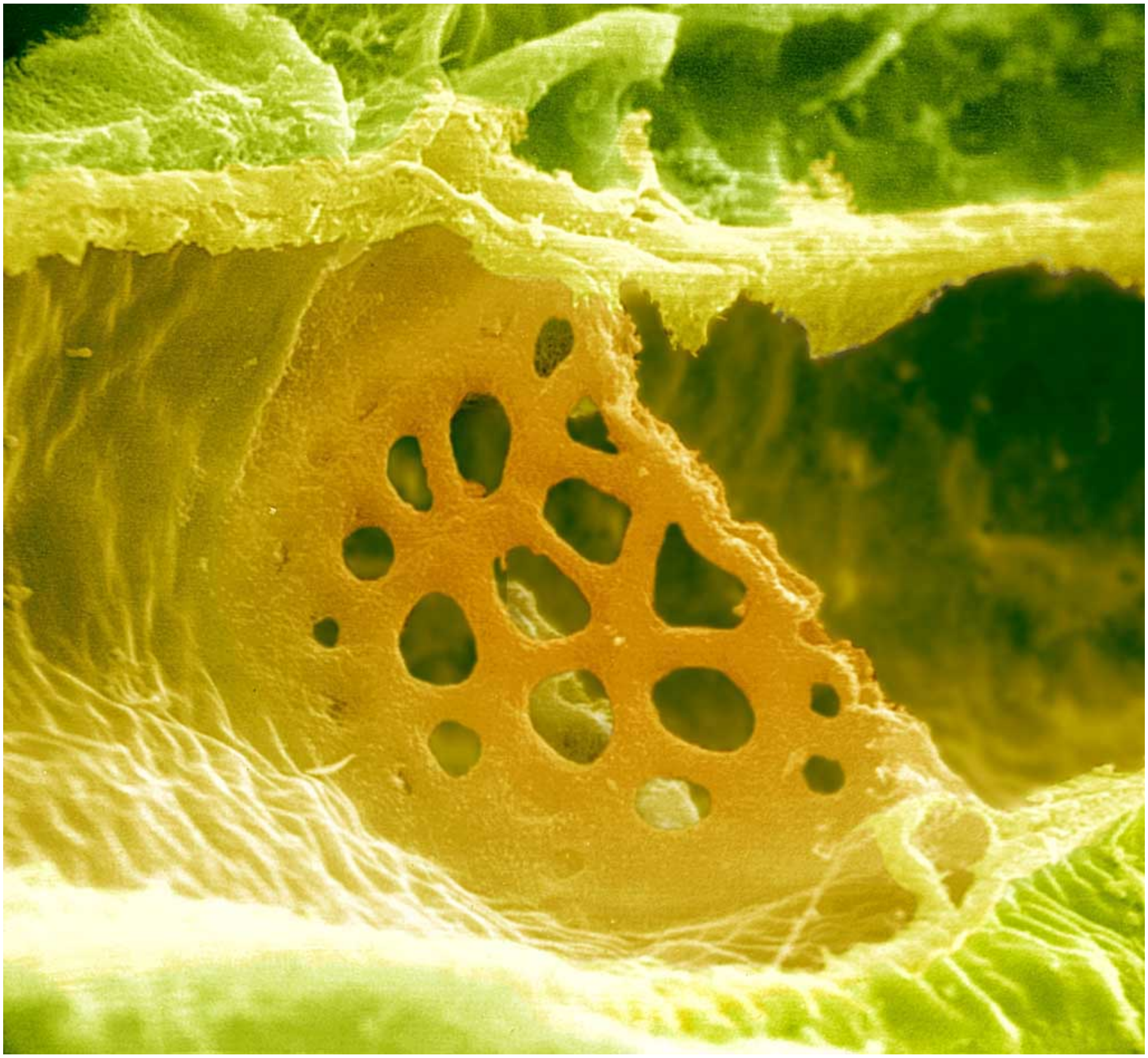


Cross-section (TEM)

Perforation plates: frontal view

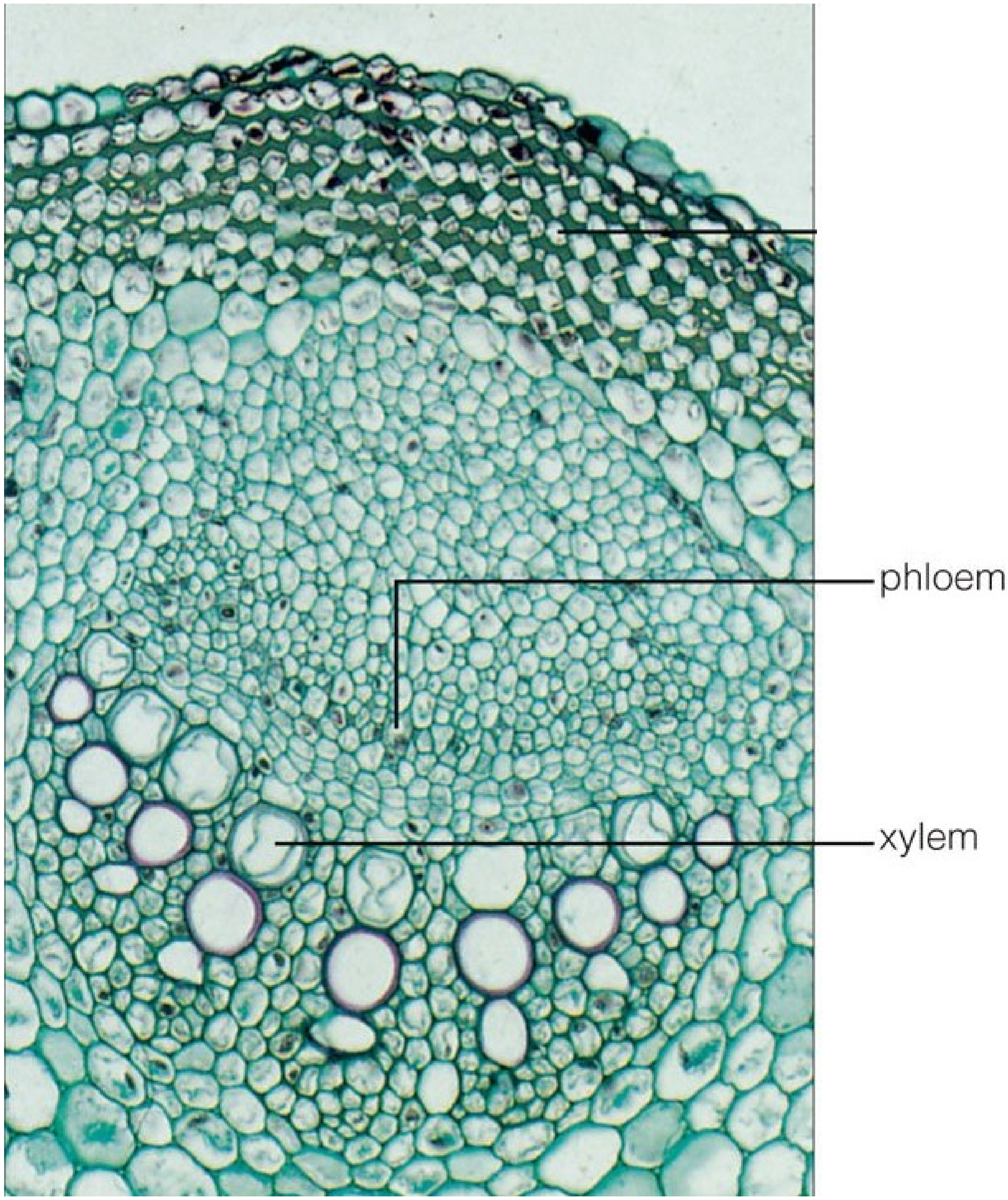

Frontal view (LM)

Plates: pores

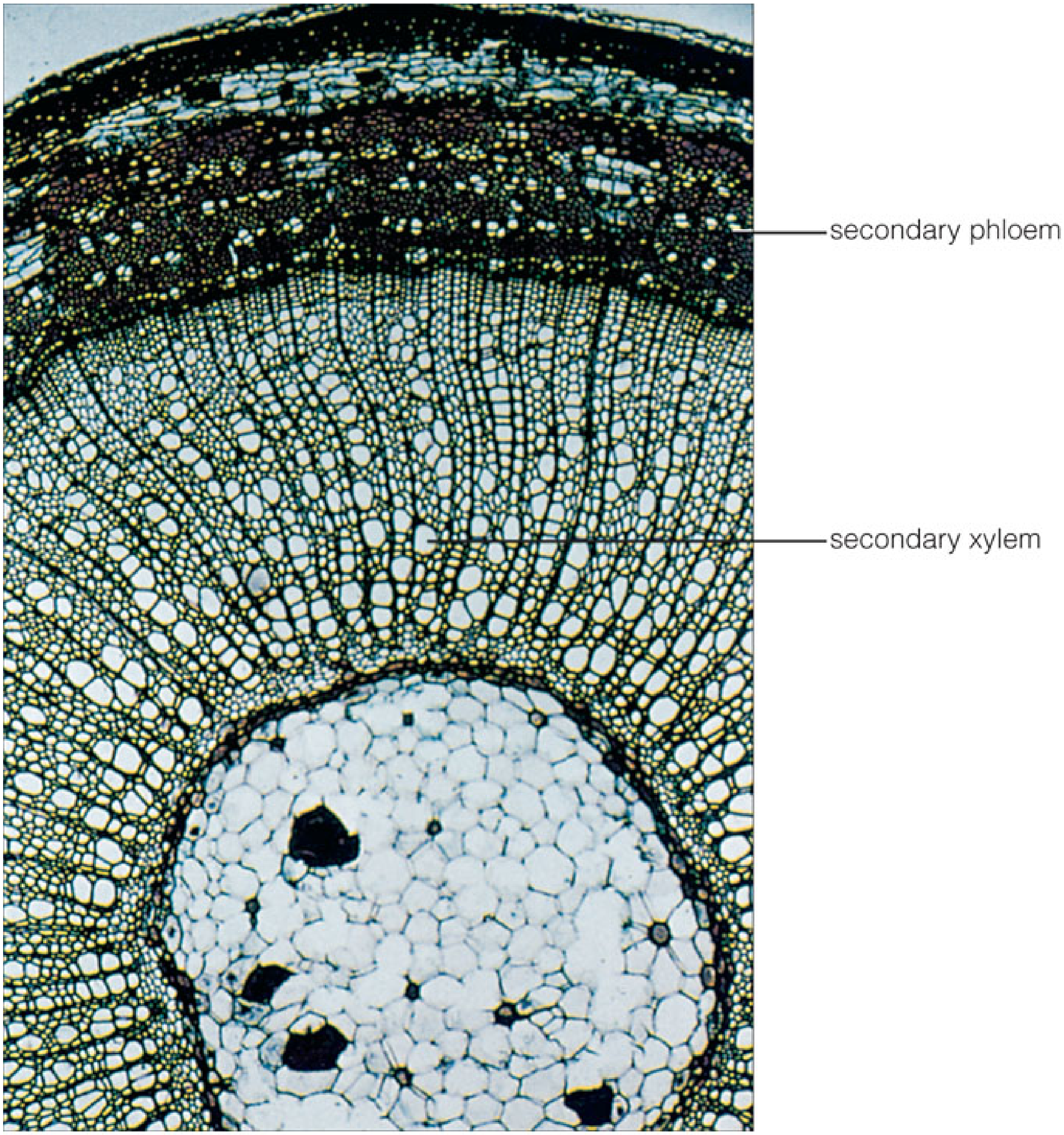


Sieve plate, a pore in the end wall of a sieve-tube member, through which phloem sap flows (SEM $\times 4800$)

Primary vascular tissues



Secondary vascular tissues

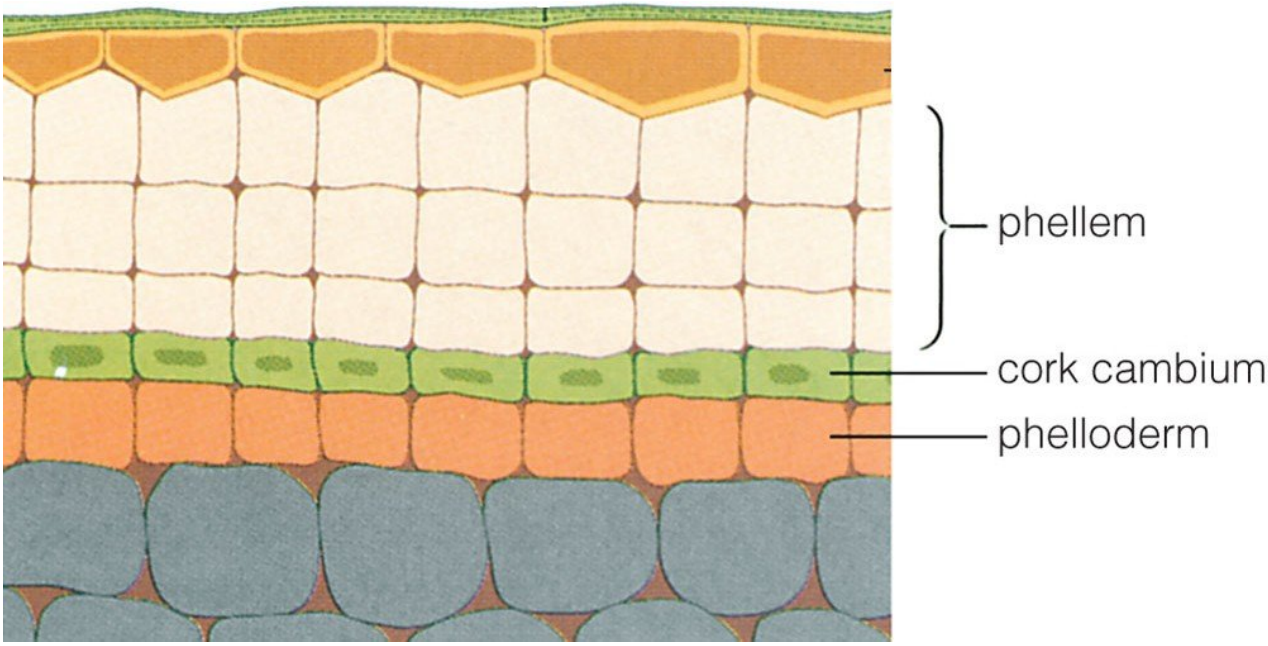


35.8 Secondary cover: periderm

Secondary dermal tissue: Periderm

- Secondary dermal tissue
- Arises inside the stem ground tissue (cortex), closer to surface
- Complex tissue: includes phellem (cork in the strict sense), cork cambium (phellogen), and phelloderm
- Old periderm includes some other tissues and becomes a bark
- Cells of phellem are dead cells rich of suberin
- Main function is defense

Three cell types of periderm



Cork cambium is another lateral meristem; *phellem* and *phelloderm* are main components of periderm

35.9 Step five: pumps. Absorption tissues

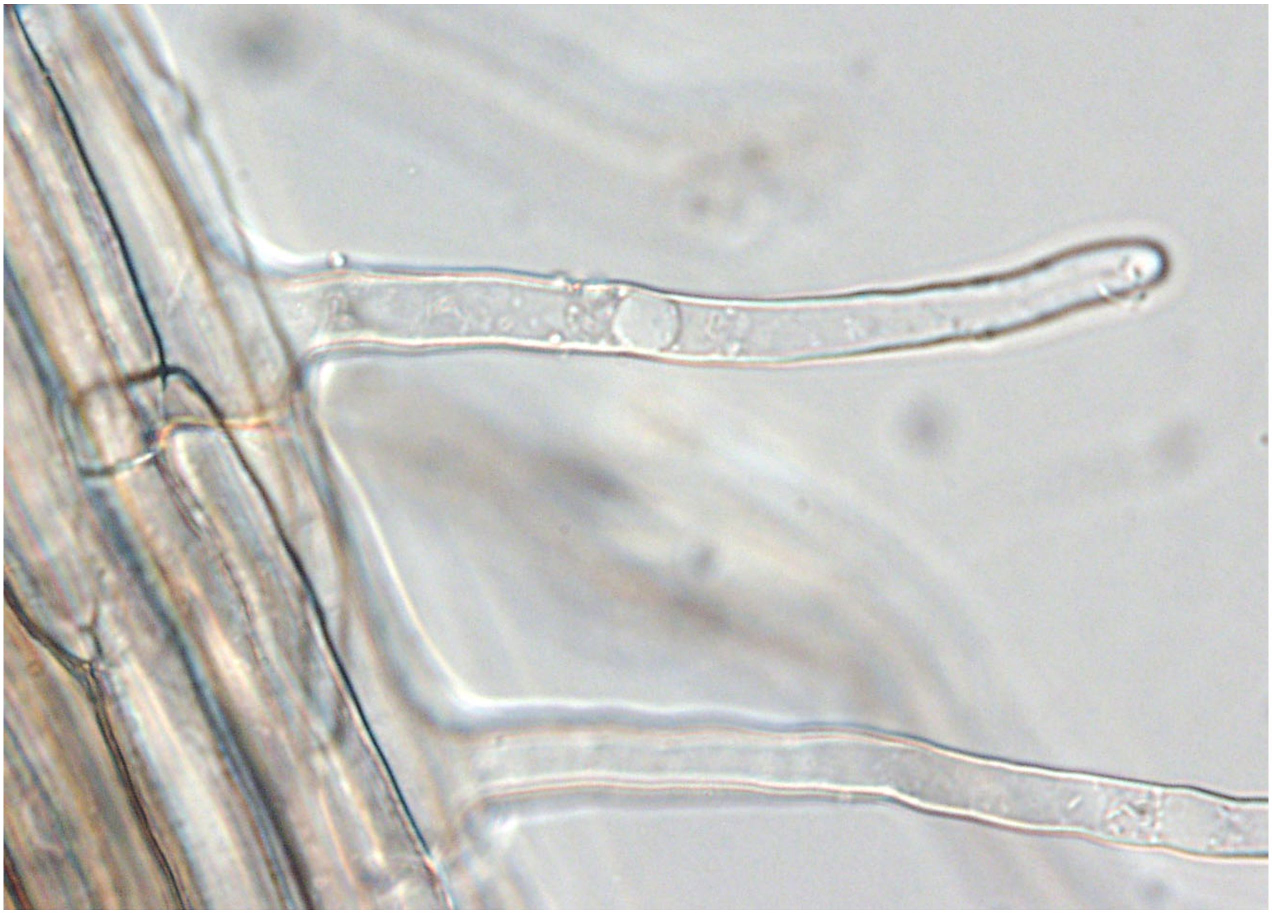
Poikilo- and homoiohydricity

- **Poikilohydric** plants do not save water, they survive even complete desiccation
- **Homoiohydric** plants save water, they always have similar water content and do not survive after desiccation
- Compare with poikilo- and homoiothermic animals (reptiles vs. mammals)

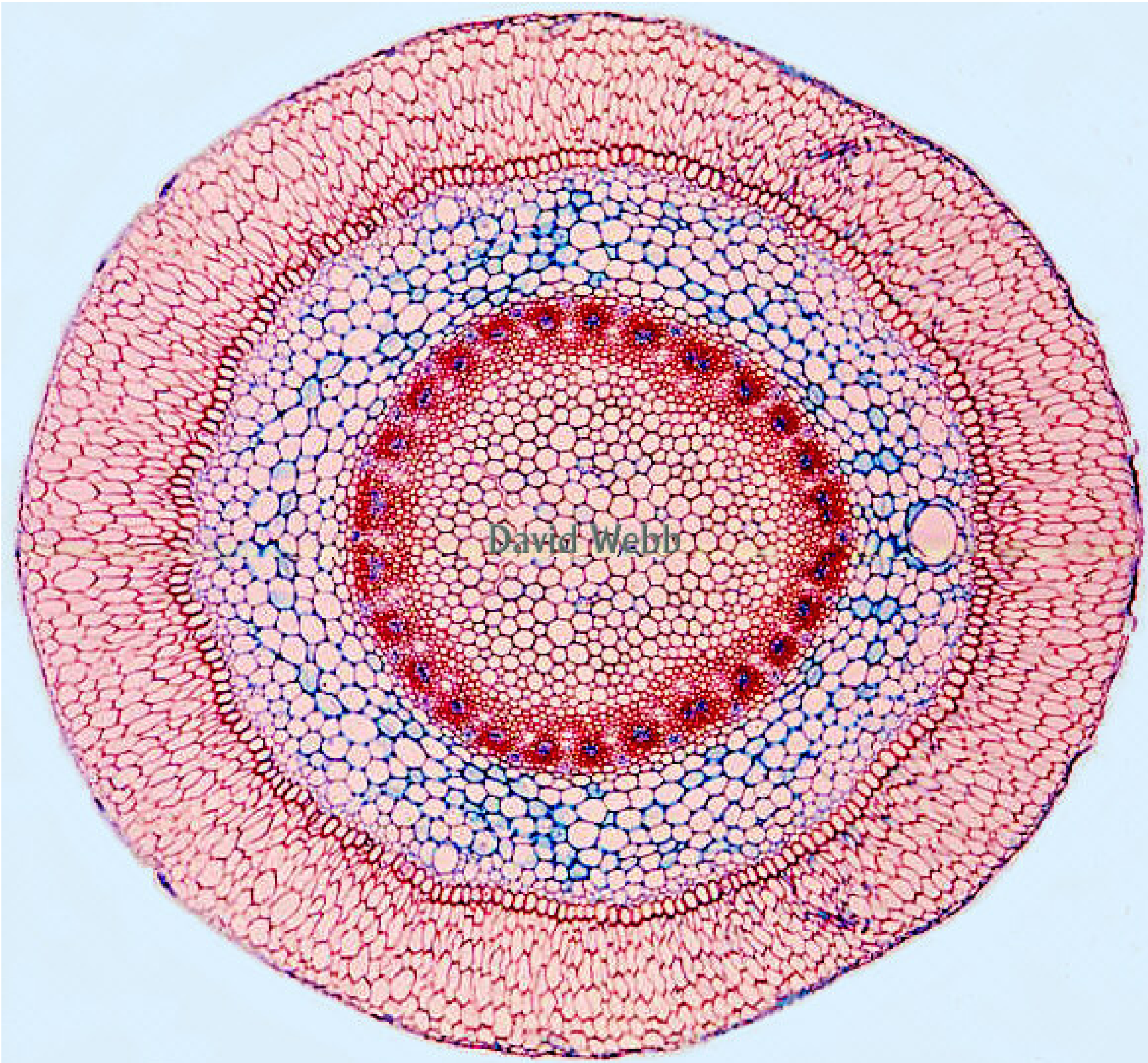
Absorption tissues

- Always primary, simple tissues
- **Rhizodermis**, or root hairs, originates from protoderm, but life span is much shorter than of epidermis
- **Velamen**, originates from root cortex

Rhizodermis


Root hairs of grass seedlings (LM)

Velamen



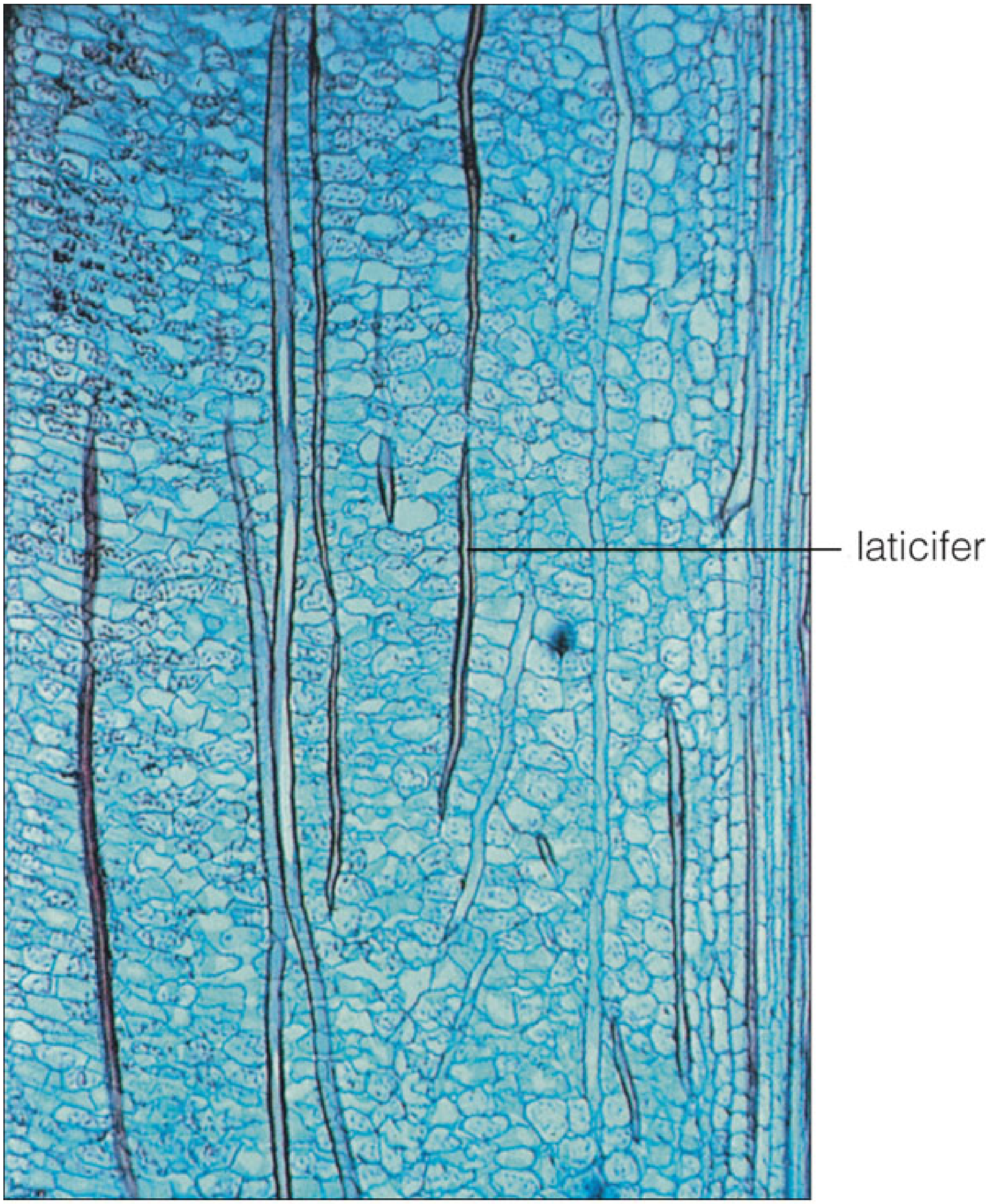
Outer cylinder is a velamen tissue of orchid root (LM)

35.10 In addition: secretory tissues

Secretory tissues

- Primary, simple or complex tissues
- Spreading across plant body, concentrating in leaves and young stems
- May secrete latex, volatile oils, mucus and other chemicals
- Functions vary: attraction or dis-attraction, communication, defense etc.

Laticifers



Quiz question (3 points)

Name 3 forces which drove plants on land.

Summary 1

- The structure of plant body, its organs and tissues is a result of land colonization
- **Complex tissues** have different cell types, **secondary tissues** originate from lateral meristems (i.e., cambium)
- **Parenchyma**, or ground tissue, is a main component of young plant organs
- **Epidermis** is a complex tissue which includes stomata

Summary 2

- **Collenchyma** and **sclerenchyma** are simple supportive tissues
- **Secondary tissues** originate from lateral meristems (i.e., cambium)
- **Xylem vs. phloem**:
  - **State**: dead vs. living cells
  - **Transport**: water vs. sugar
  - **Direction**: up vs. down
  - **Biomass**: big vs. small

For Further Reading

References

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

Outline

36 Questions and answers

36.1 Quiz

Quiz question (3 points)

Name 3 forces which drove plants on land

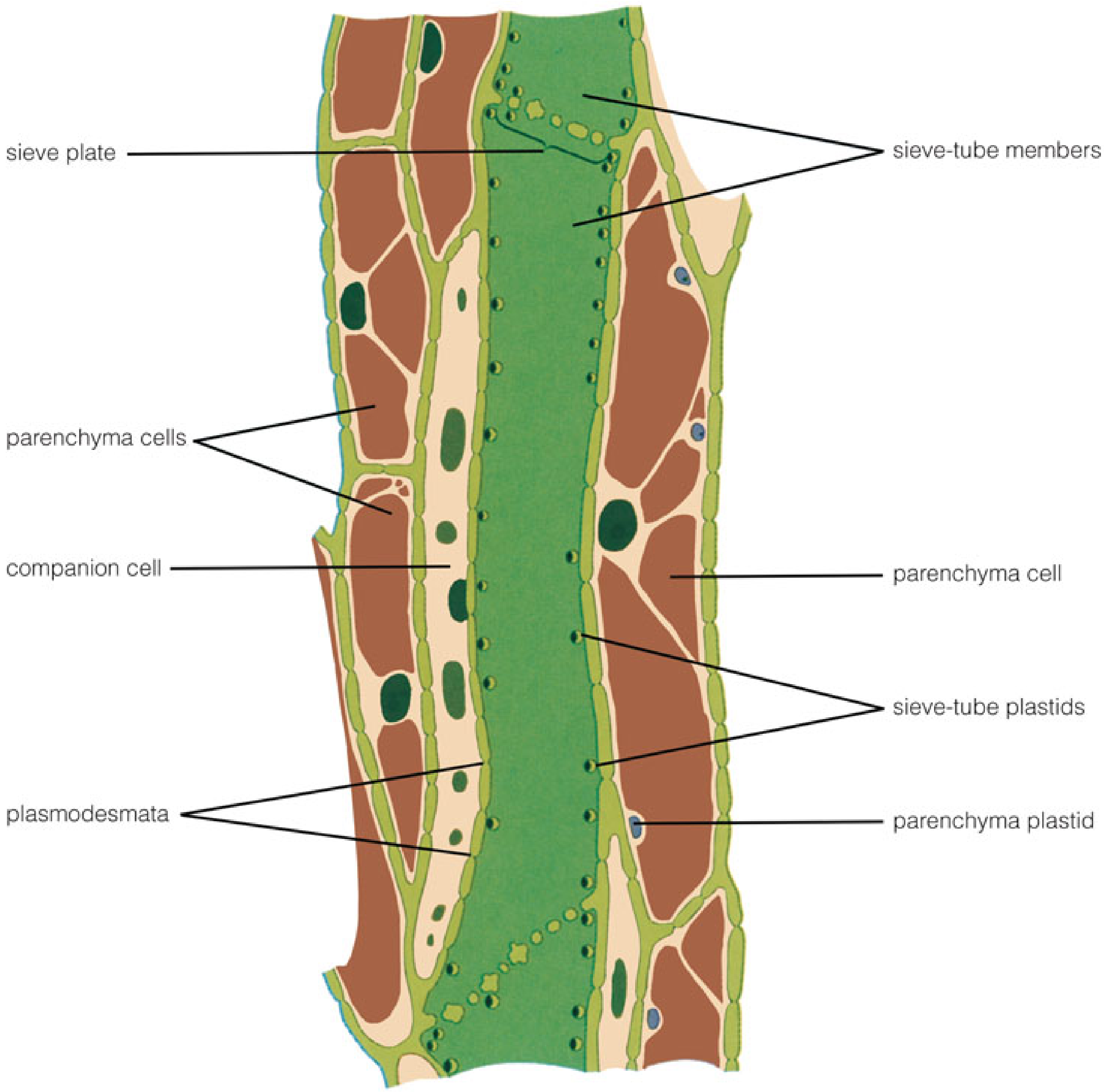
- Competition between plants
- General availability of light
- Temperature / gas conflict (or how hungry whales and coke relate)

36.1.1 Phloem

Phloem

- Usually occurs adjacent to a xylem
- Types of cells: **sieve tube cells**, **companion cells**, **fibers** and **parenchyma**
- Sieve tube cells have plastids and perforation (sieve) plates between cells but no nuclei, companion cells have nuclei
- However, in gymnosperms there are *no* companion cells and sieve tube cells *have* nuclei
- Secondary phloem usually has more fibers than primary phloem
- Main functions: sugar transport and mechanical support

Phloem cell types



Sieve tubes and phloem parenchyma

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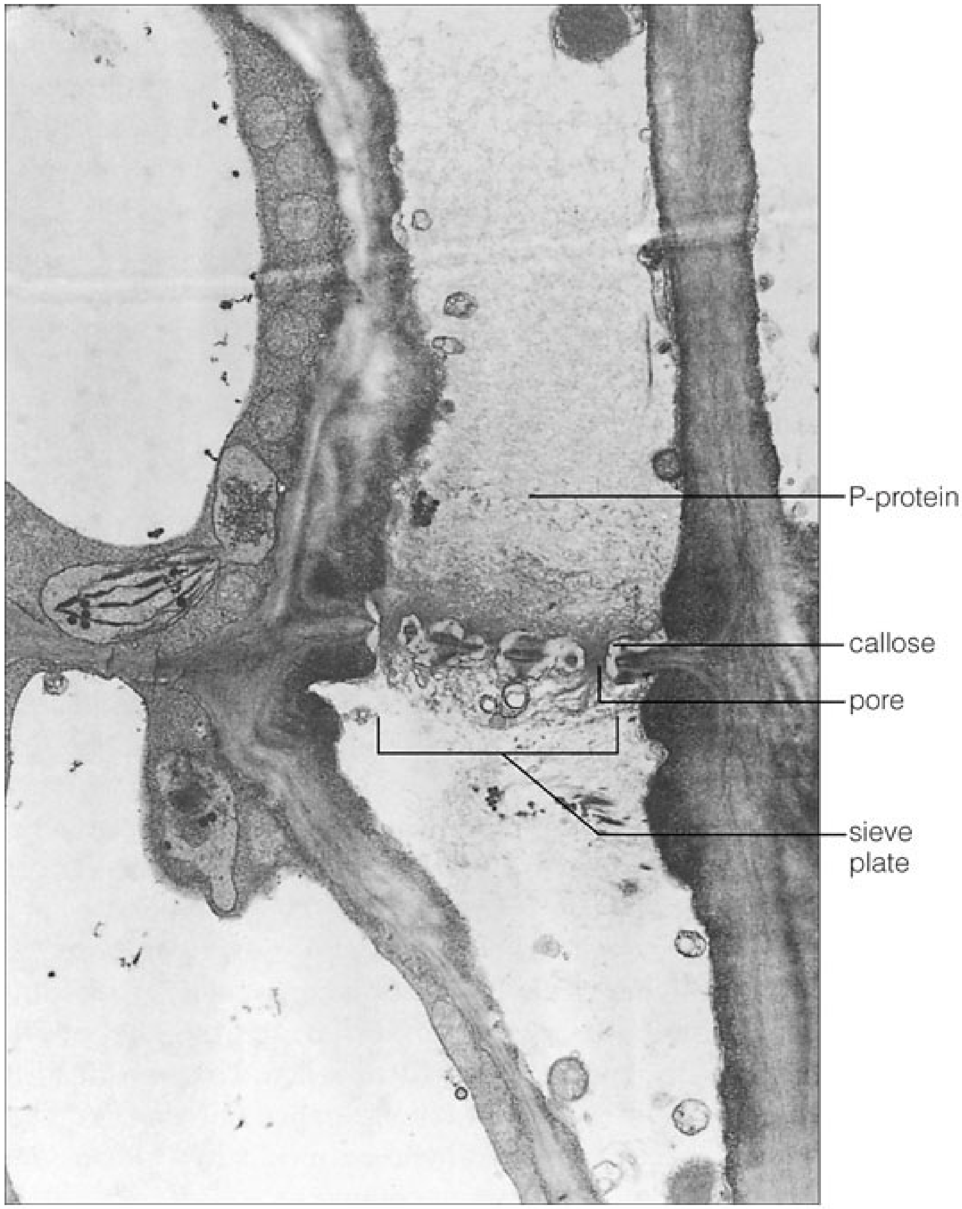

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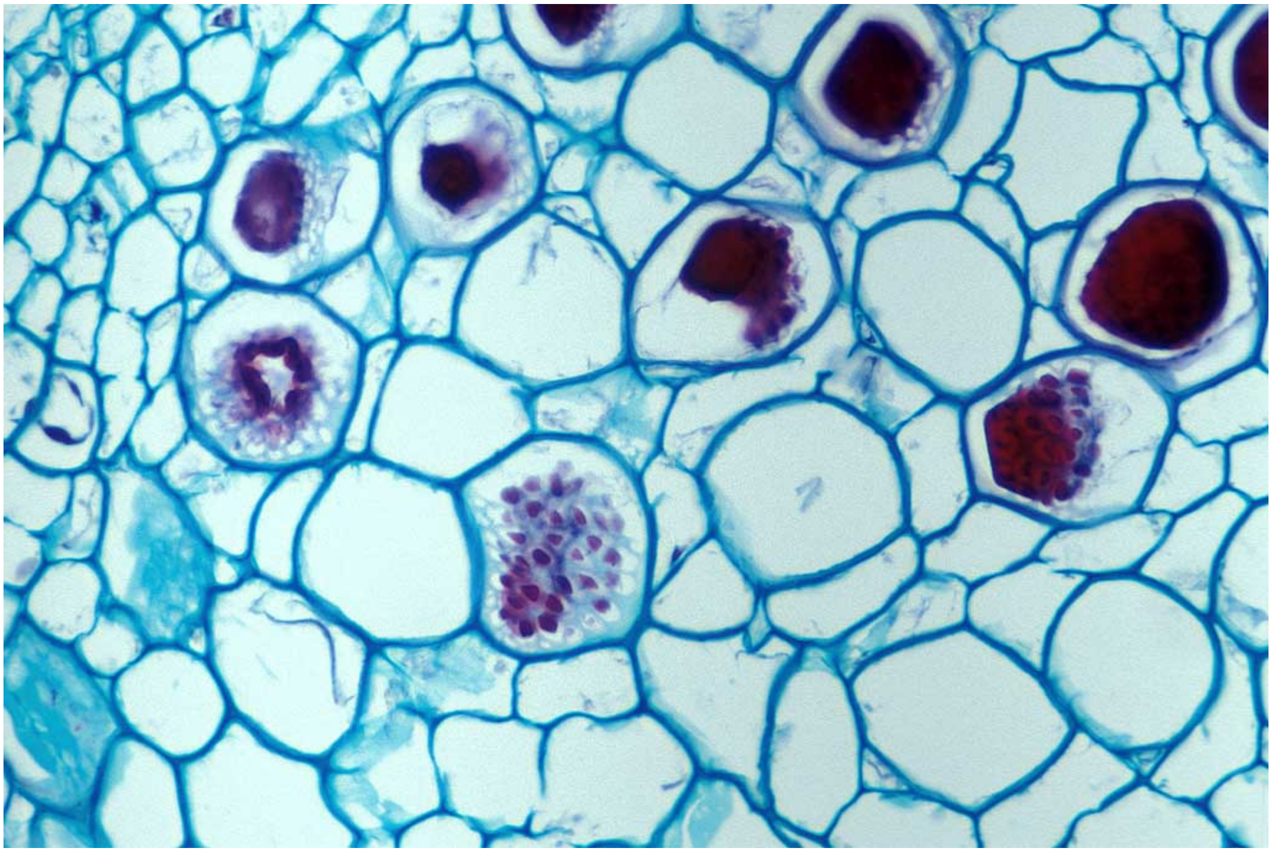
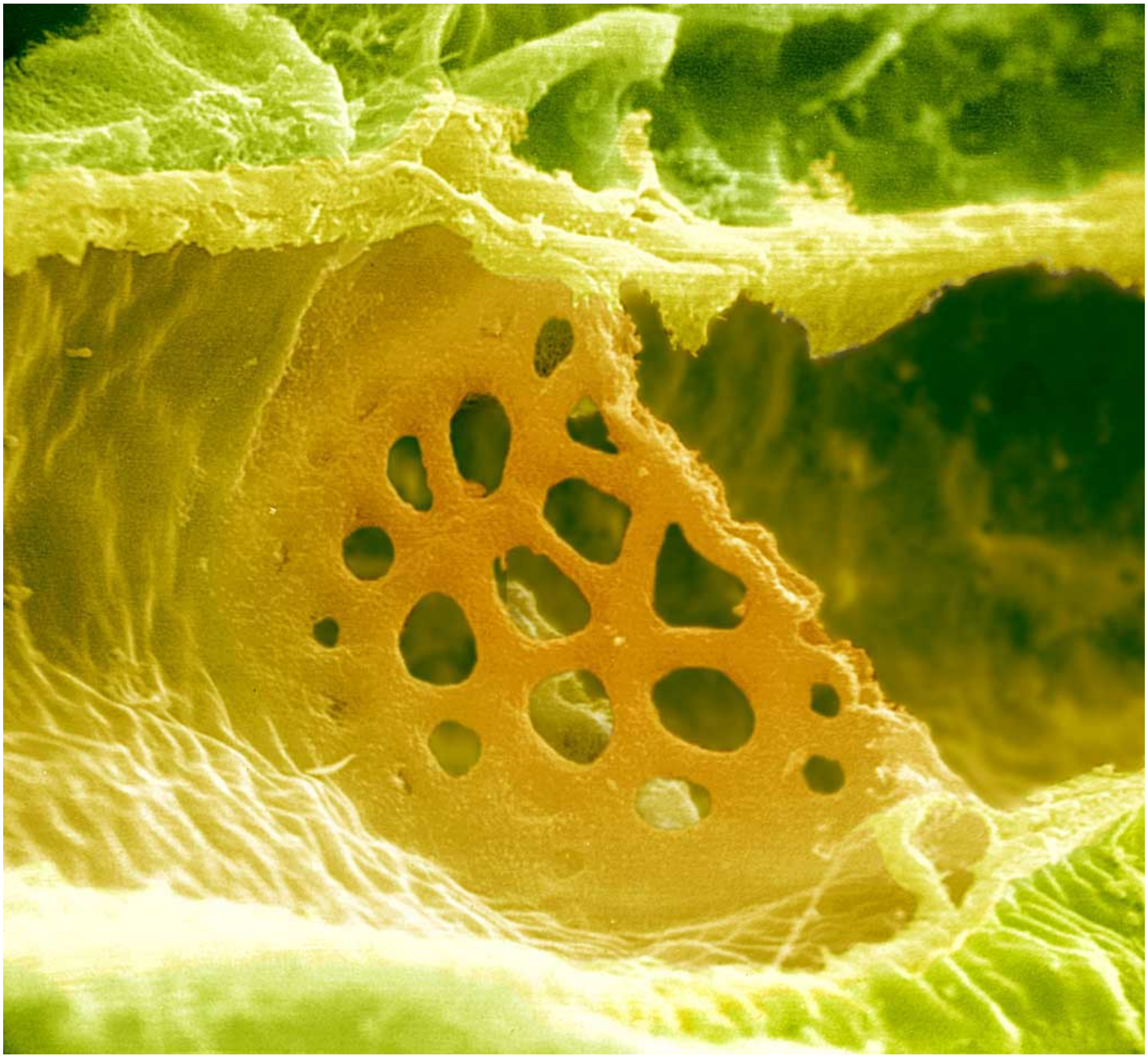
Perforation plates: frontal view



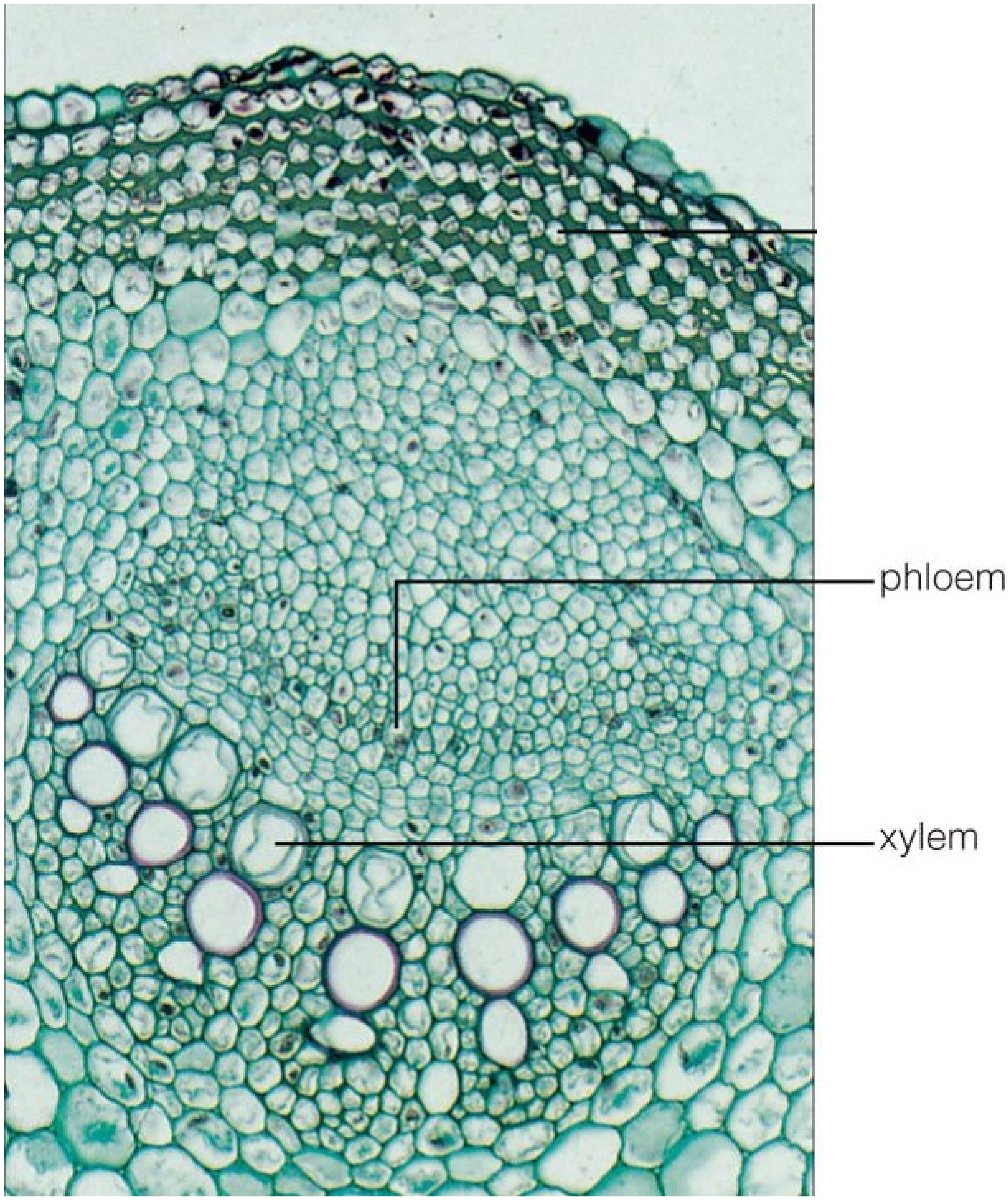
Frontal view (LM)

Plates: pores

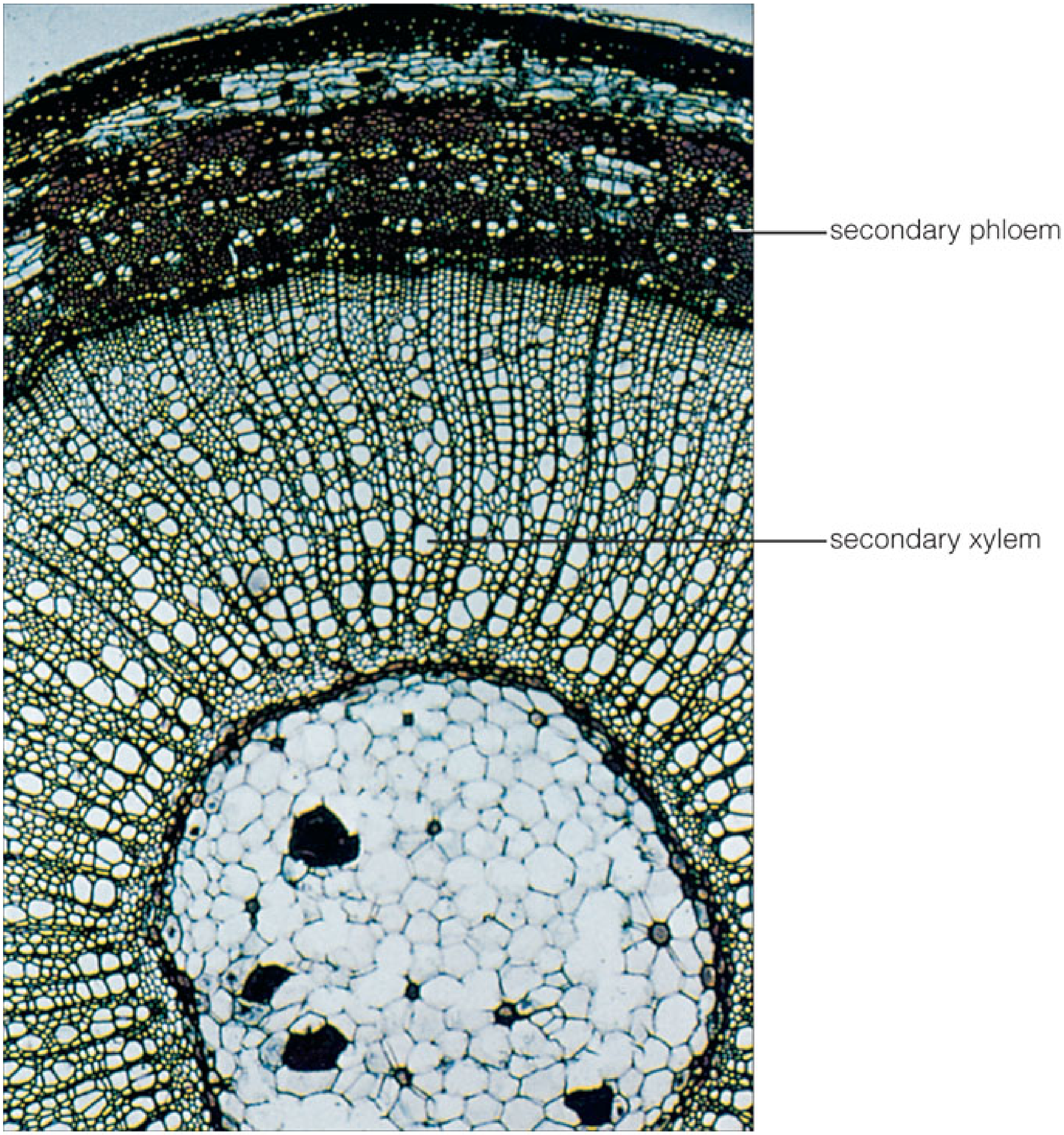


Sieve plate, a pore in the end wall of a sieve-tube member, through which phloem sap flows (SEM ×4800)

Primary vascular tissues



Secondary vascular tissues



36.2 Secondary cover: periderm

Secondary dermal tissue: Periderm

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- Complex tissue: includes phellem (cork in the strict sense), cork cambium (phellogen), and phelloderm
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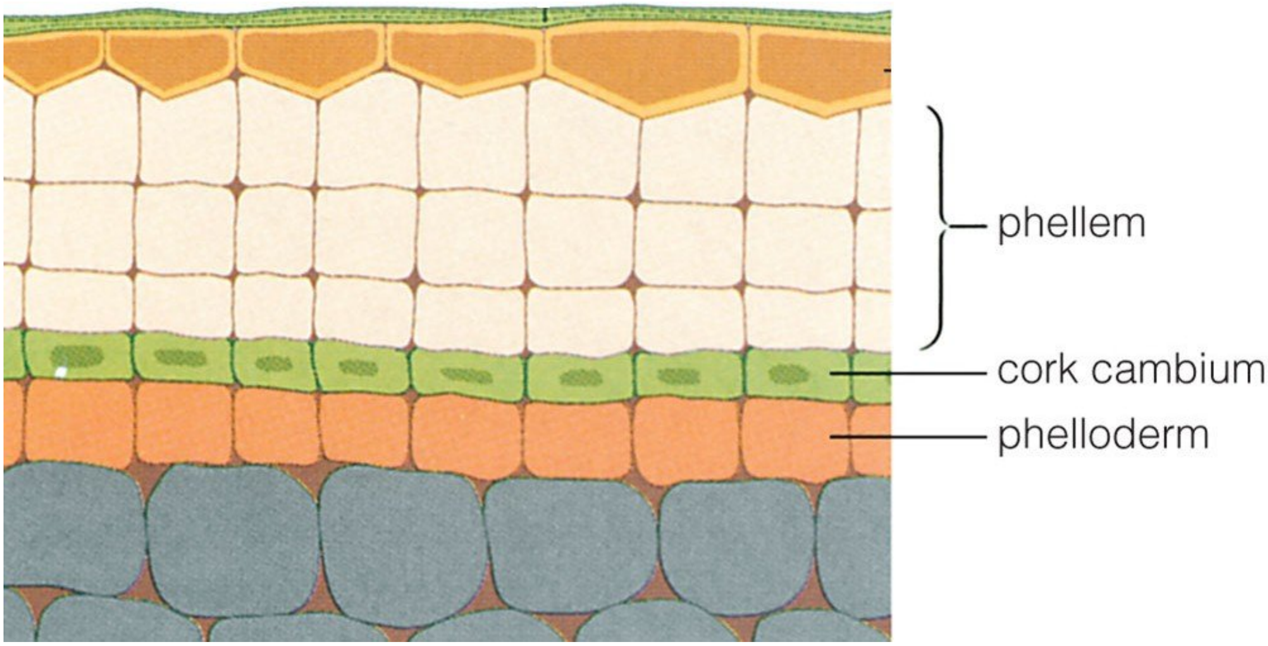
Three cell types of periderm



Cork cambium is another lateral meristem; *phellem* and *phelloderm* are main components of periderm

36.3 Step five: pumps. Absorption tissues

Poikilo- and homoiohydricity

- **Poikilohydric** plants do not save water, they survive even complete desiccation
- **Homoiohydric** plants save water, they always have similar water content and do not survive after desiccation
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Absorption tissues

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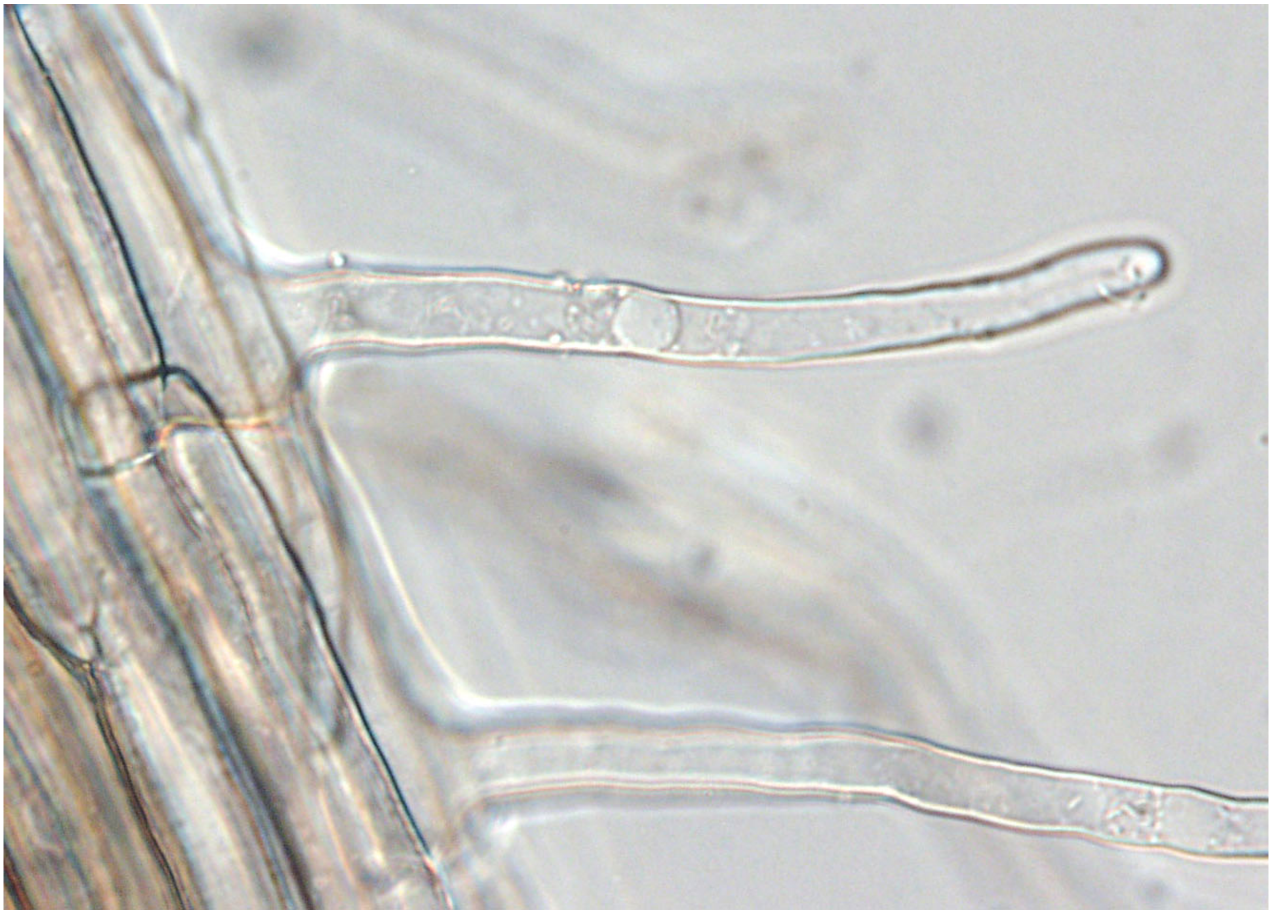
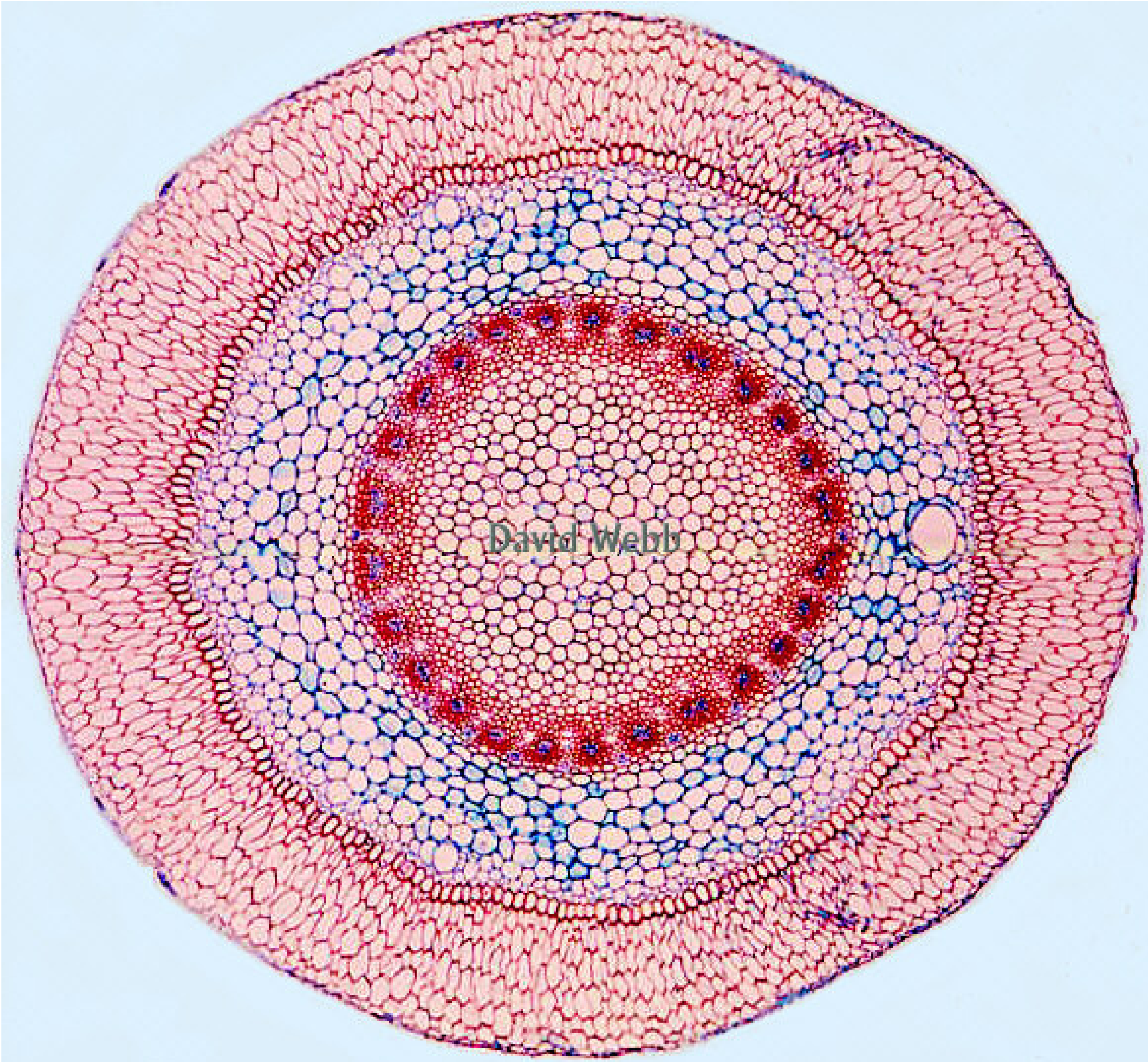
- **Rhizodermis**, or root hairs, originates from protoderm, but life span is much shorter than of epidermis
- **Velamen**, originates from root cortex

Rhizodermis



Root hairs of grass seedlings (LM)

Velamen



Outer cylinder is a velamen tissue of orchid root (LM)

36.4 In addition: secretory tissues

Secretory tissues

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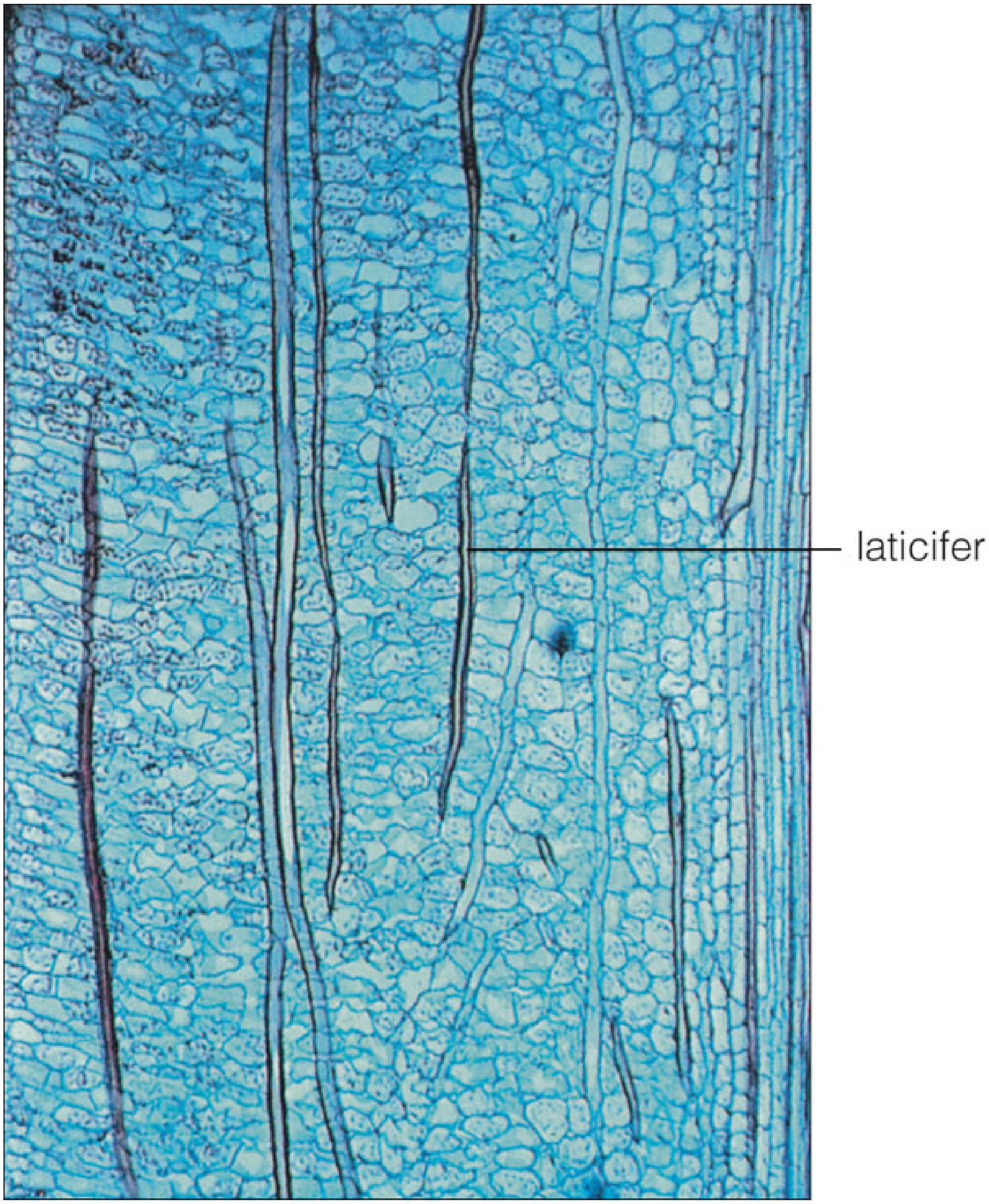
- Spreading across plant body, concentrating in leaves and young stems
- May secrete latex, volatile oils, mucus and other chemicals
- Functions vary: attraction or dis-attraction, communication, defense etc.

Laticifers



Summary

- **Epidermis** is a complex tissue which includes stomata
- **Collenchyma** and **sclerenchyma** are simple supportive tissues
- **Secondary tissues** originate from lateral meristems (i.e., cambium)
- **Xylem vs. phloem**:
  - **State**: dead vs. living cells
  - **Transport**: water vs. sugar
  - **Direction**: up vs. down
  - **Biomass**: big vs. small

Final question (3 points)

Name 3 differences between xylem and phloem.

For Further Reading

References

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

Outline

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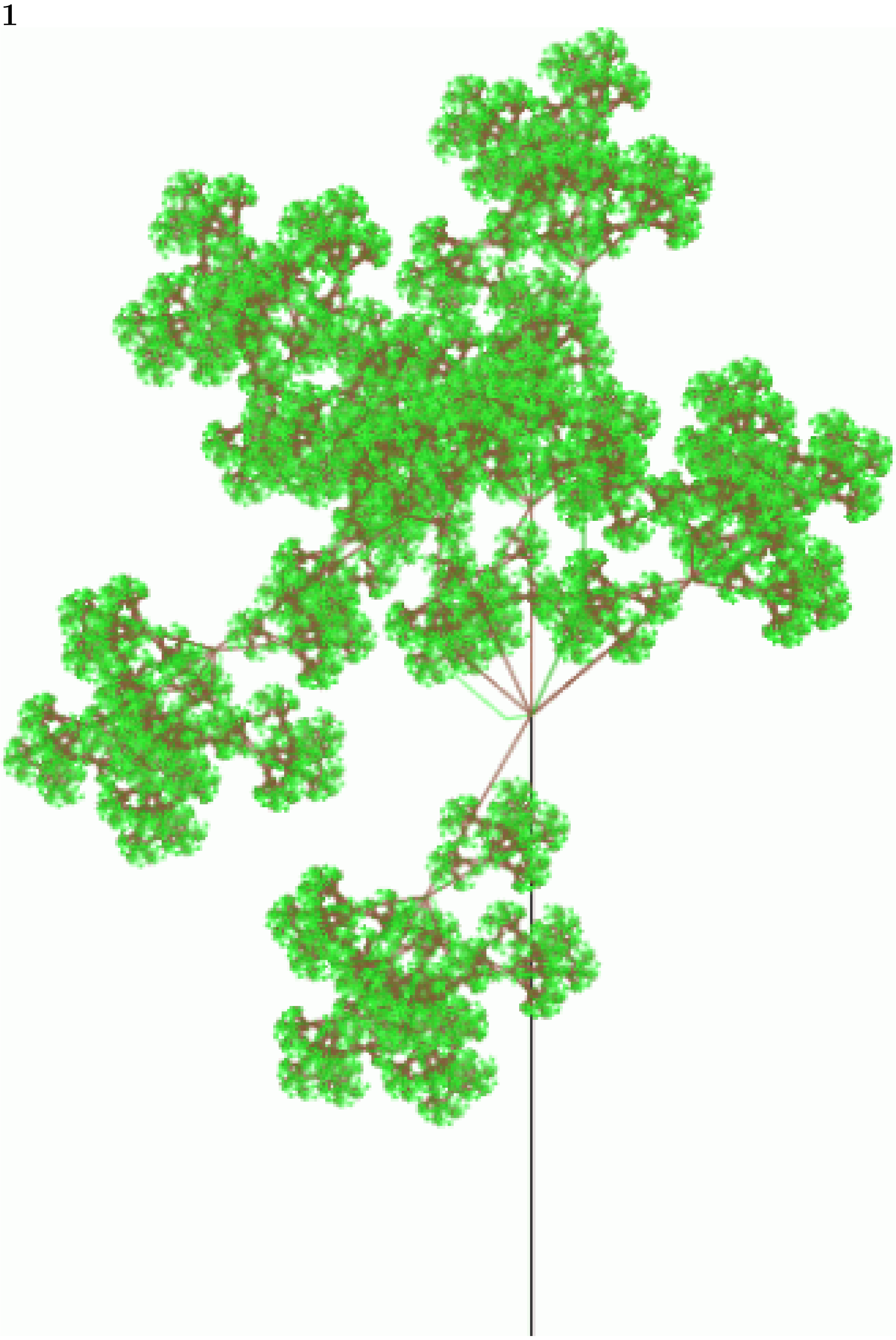

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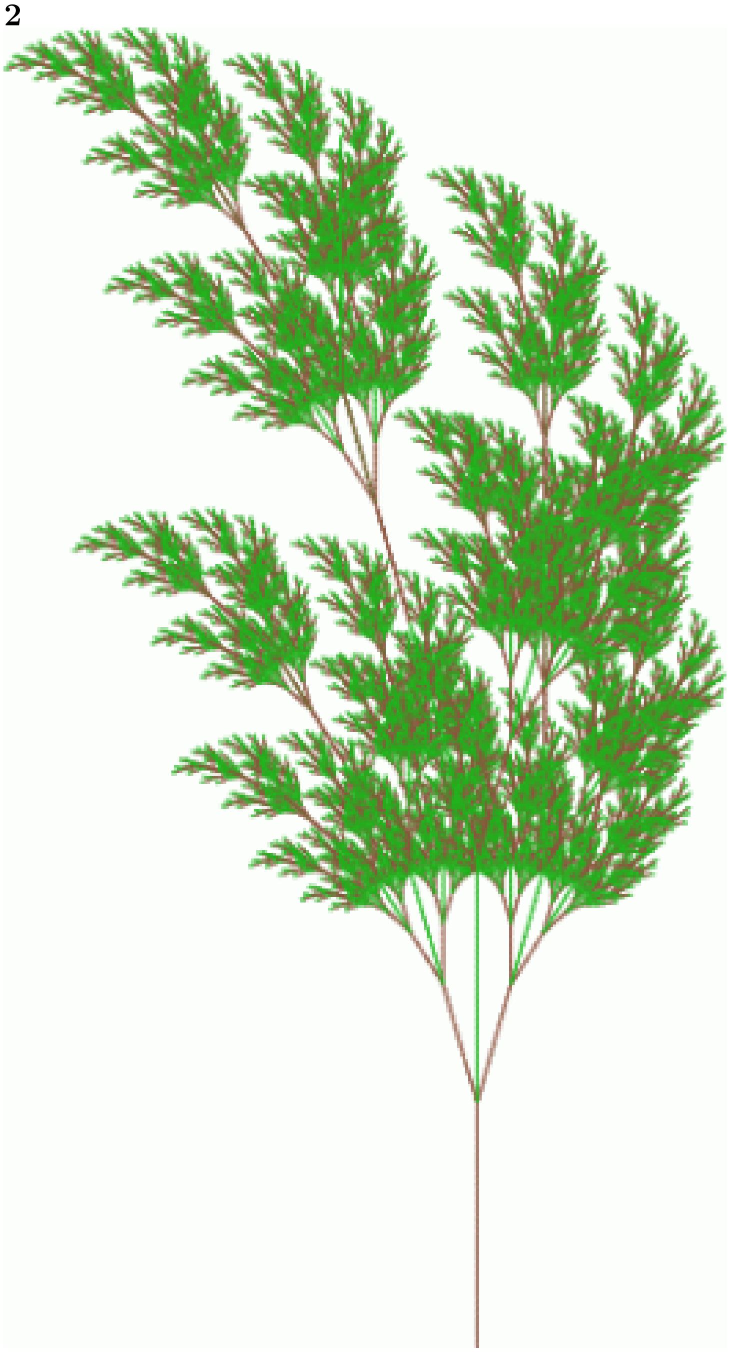

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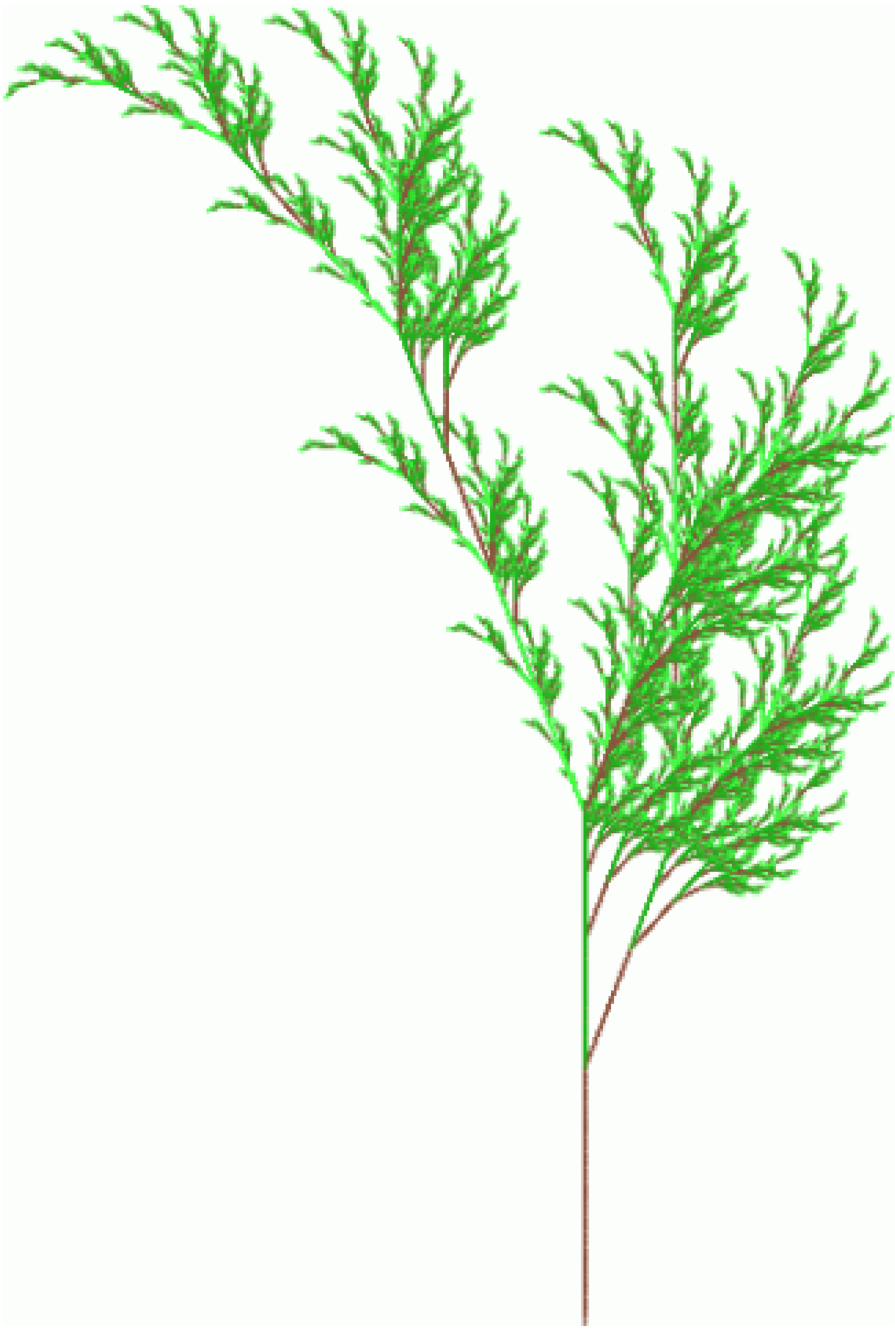

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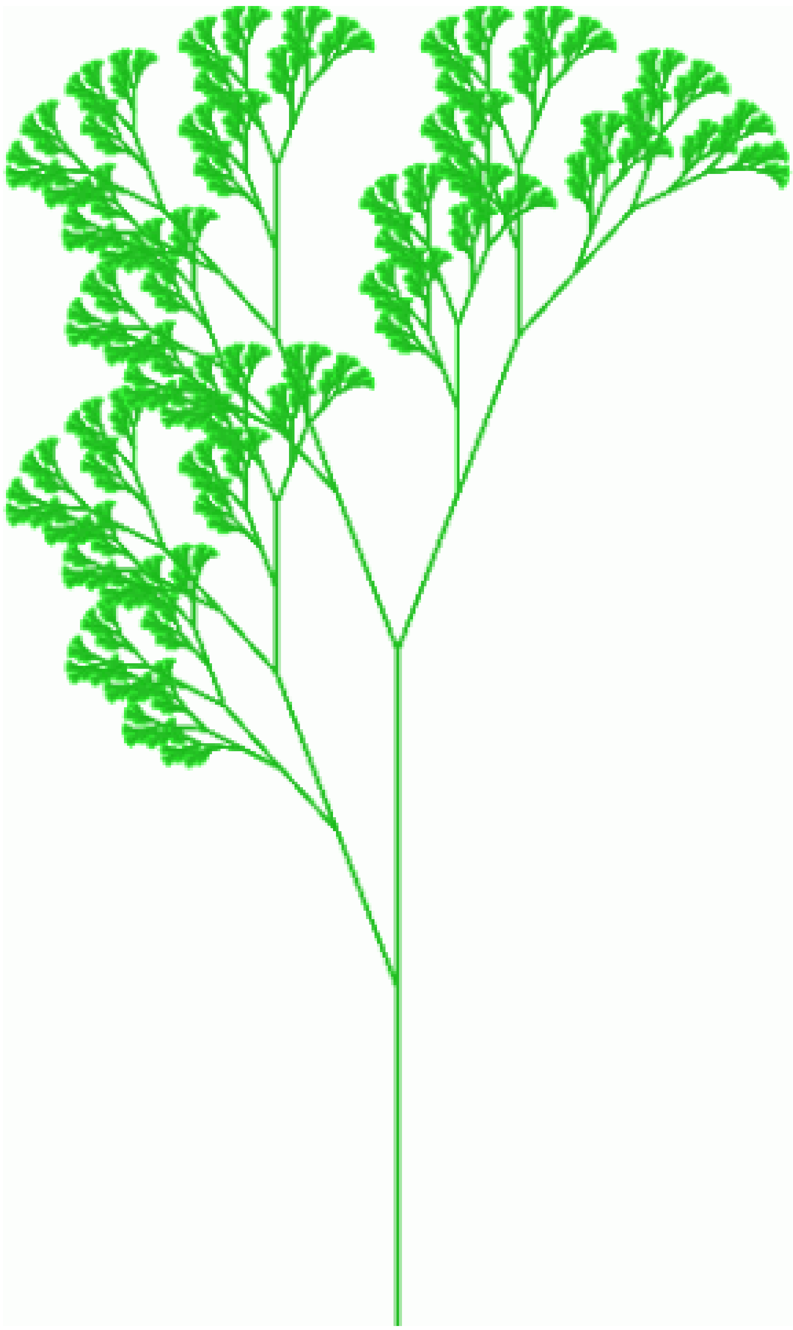

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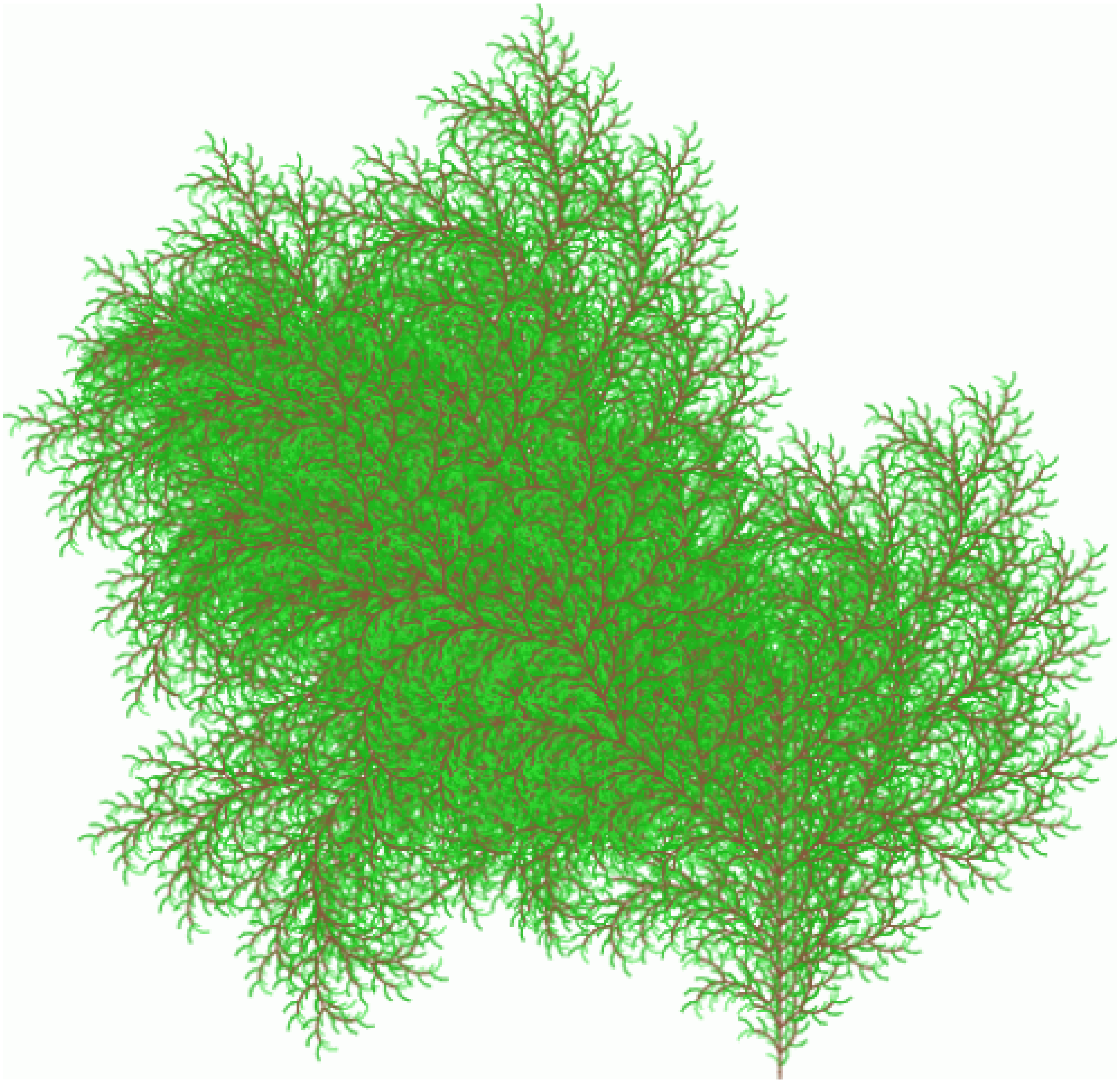

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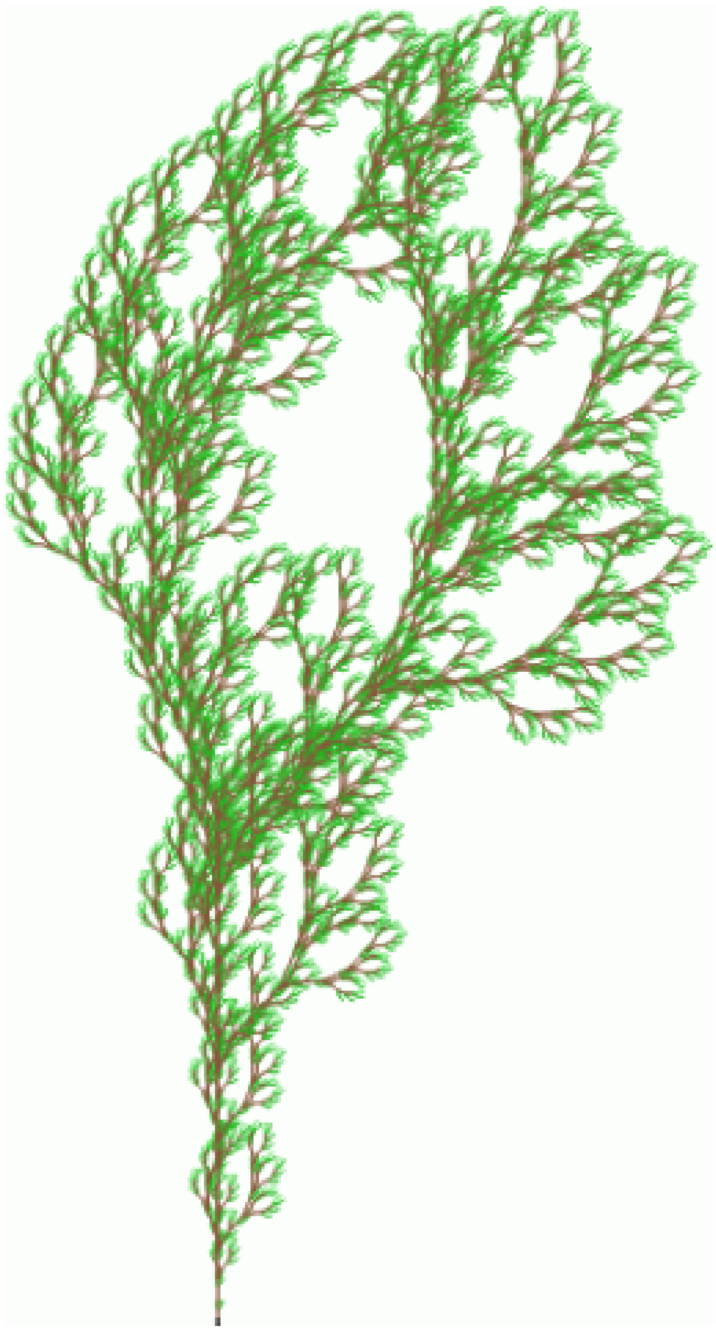

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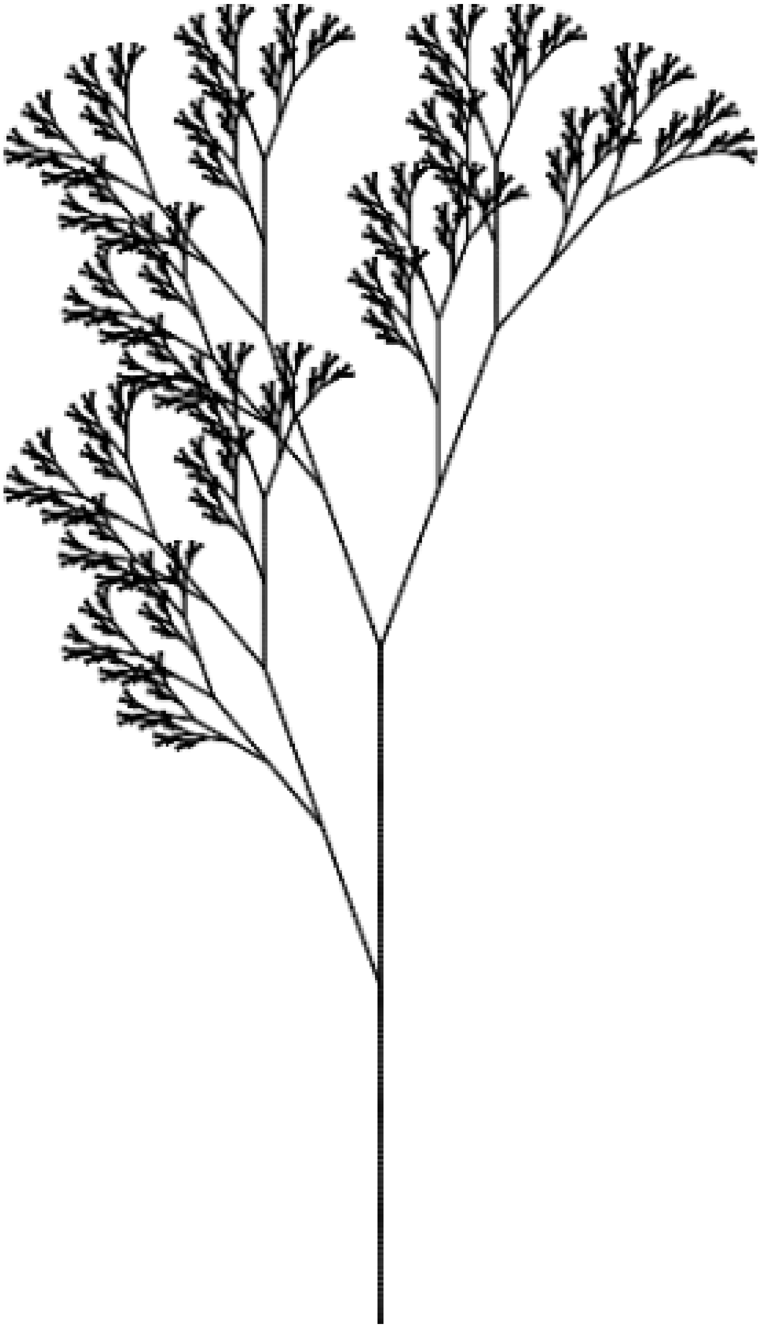

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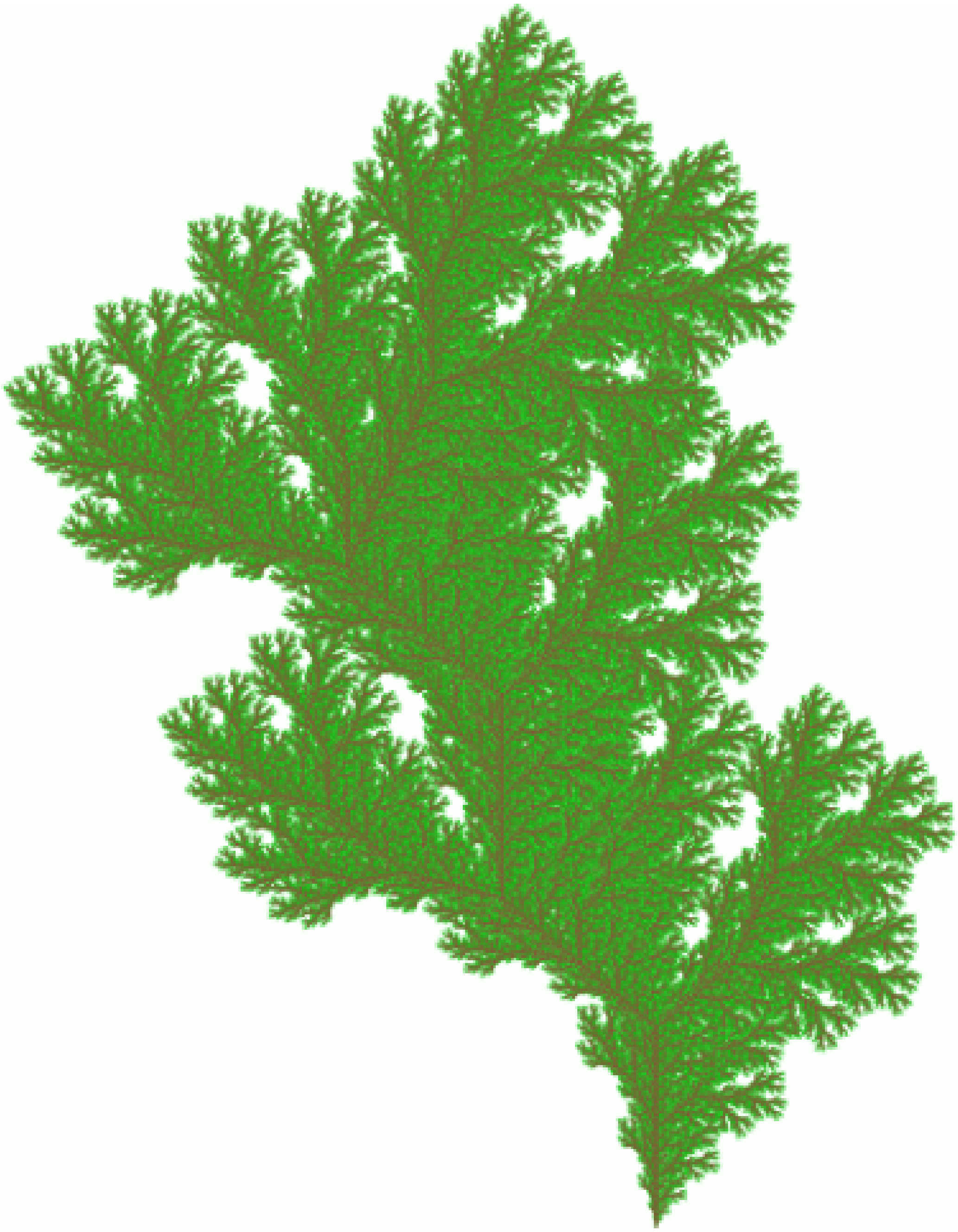

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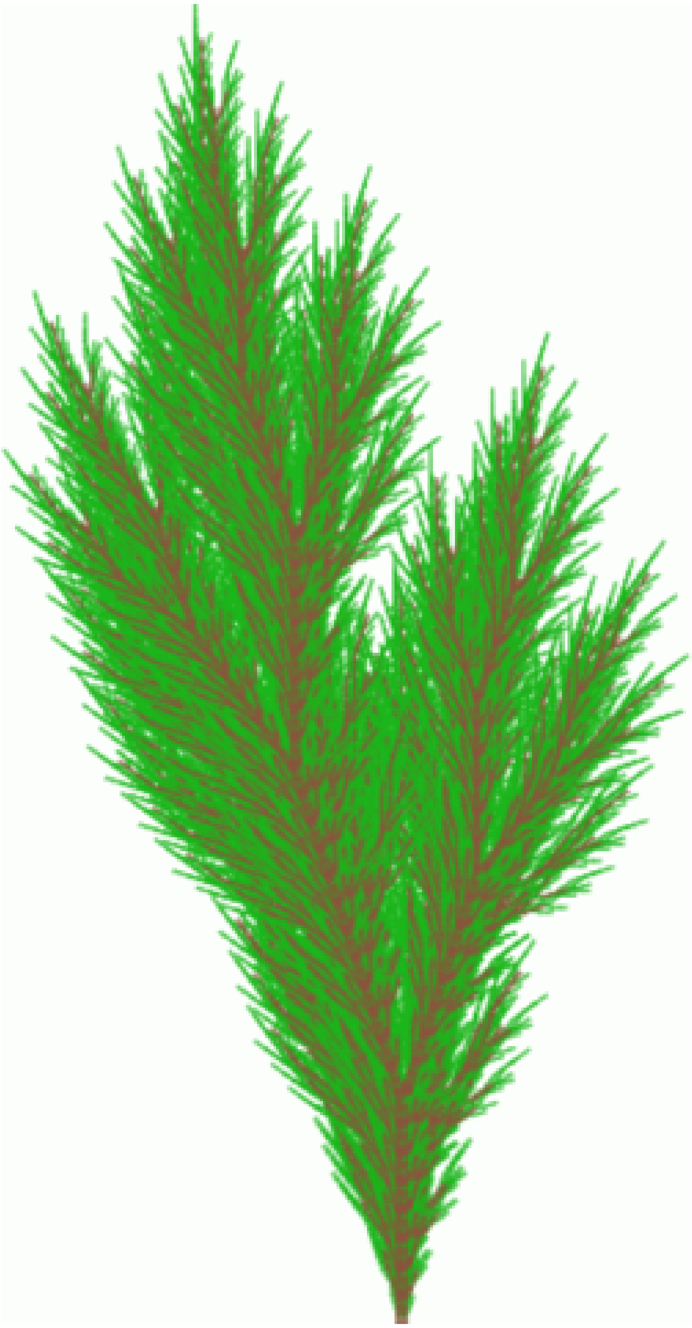

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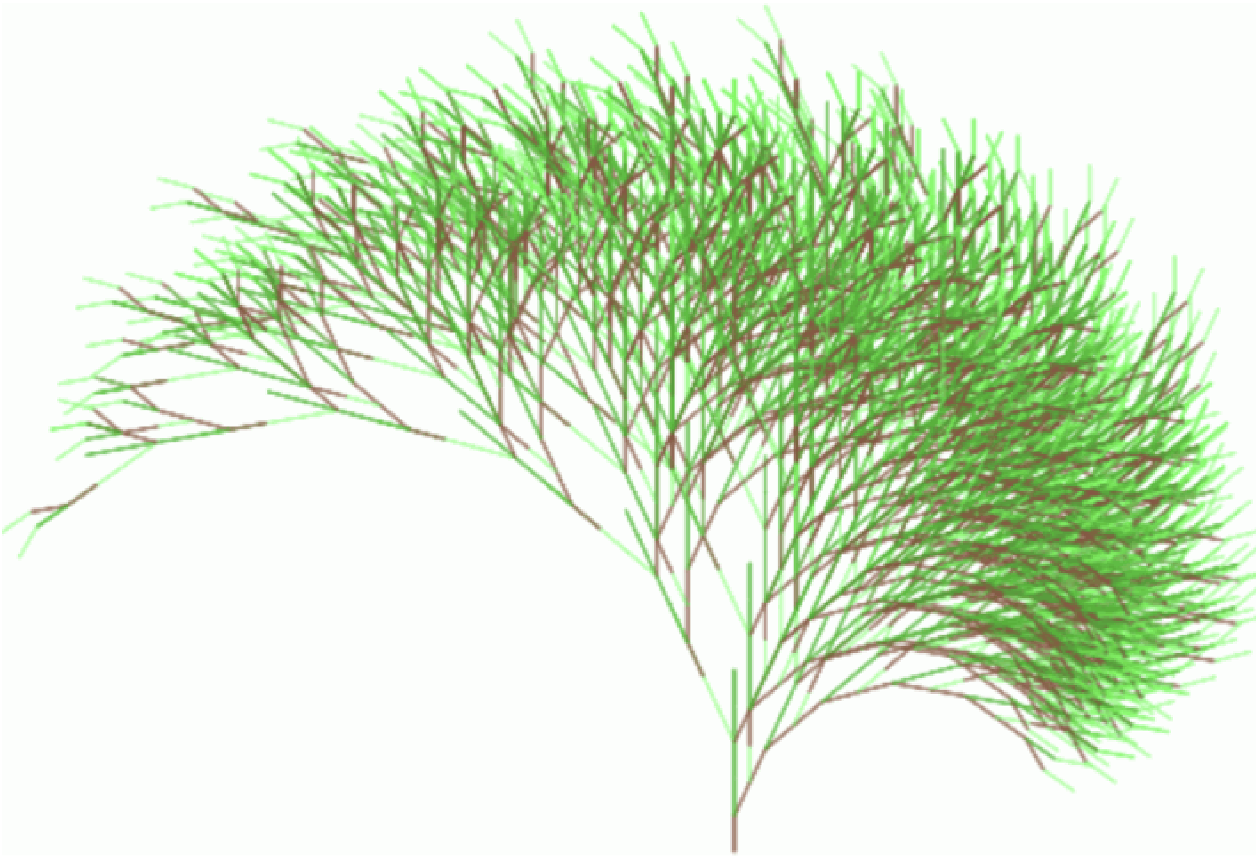

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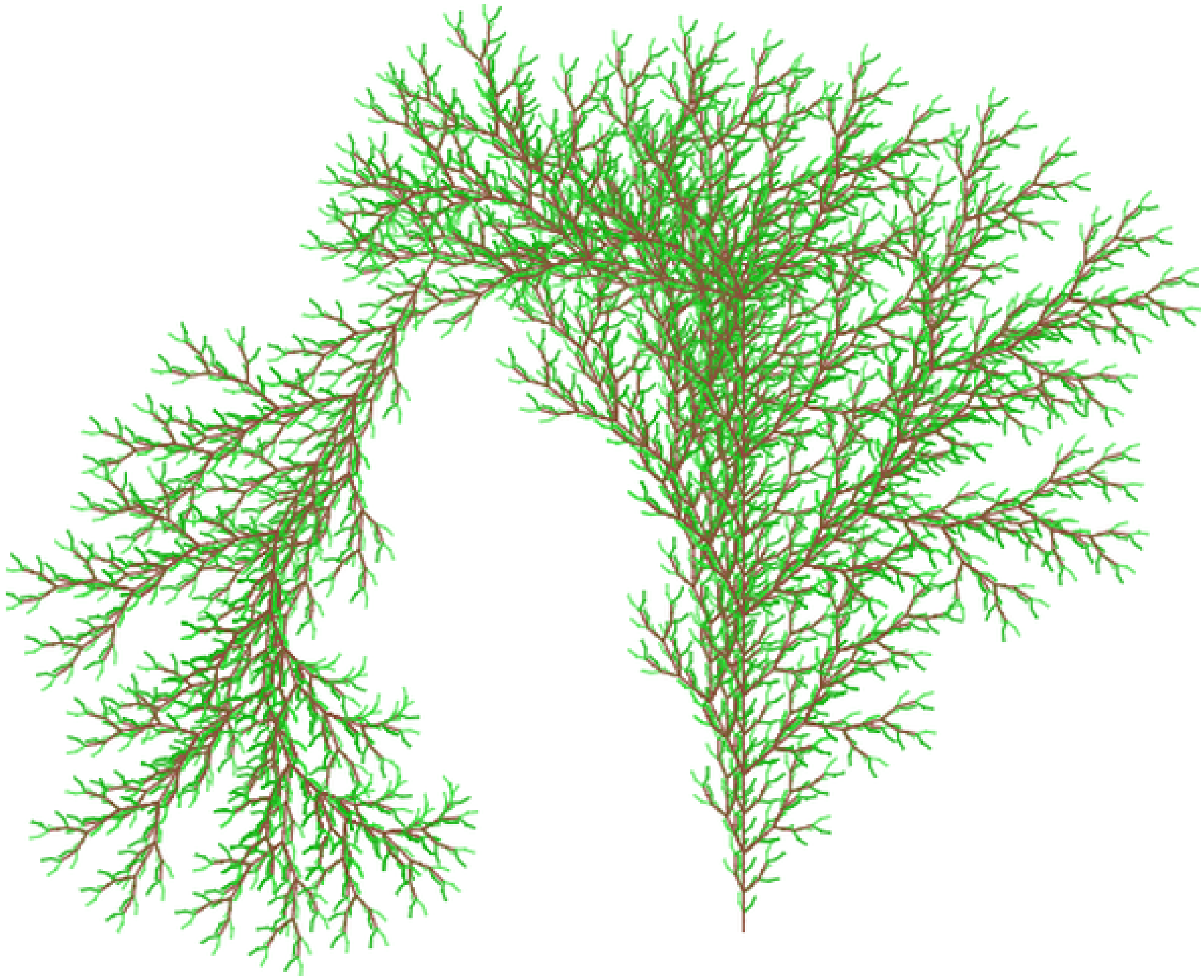

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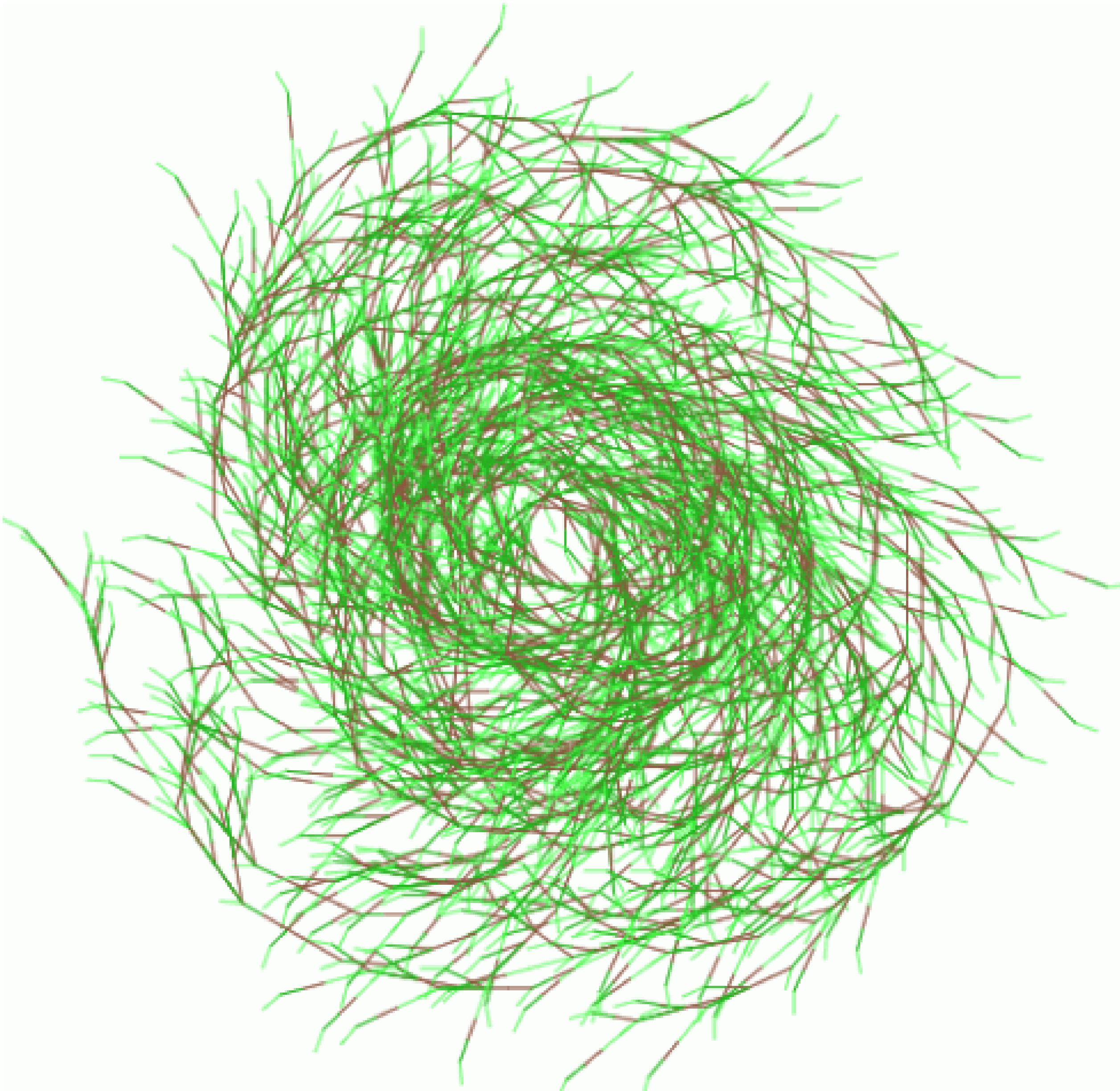

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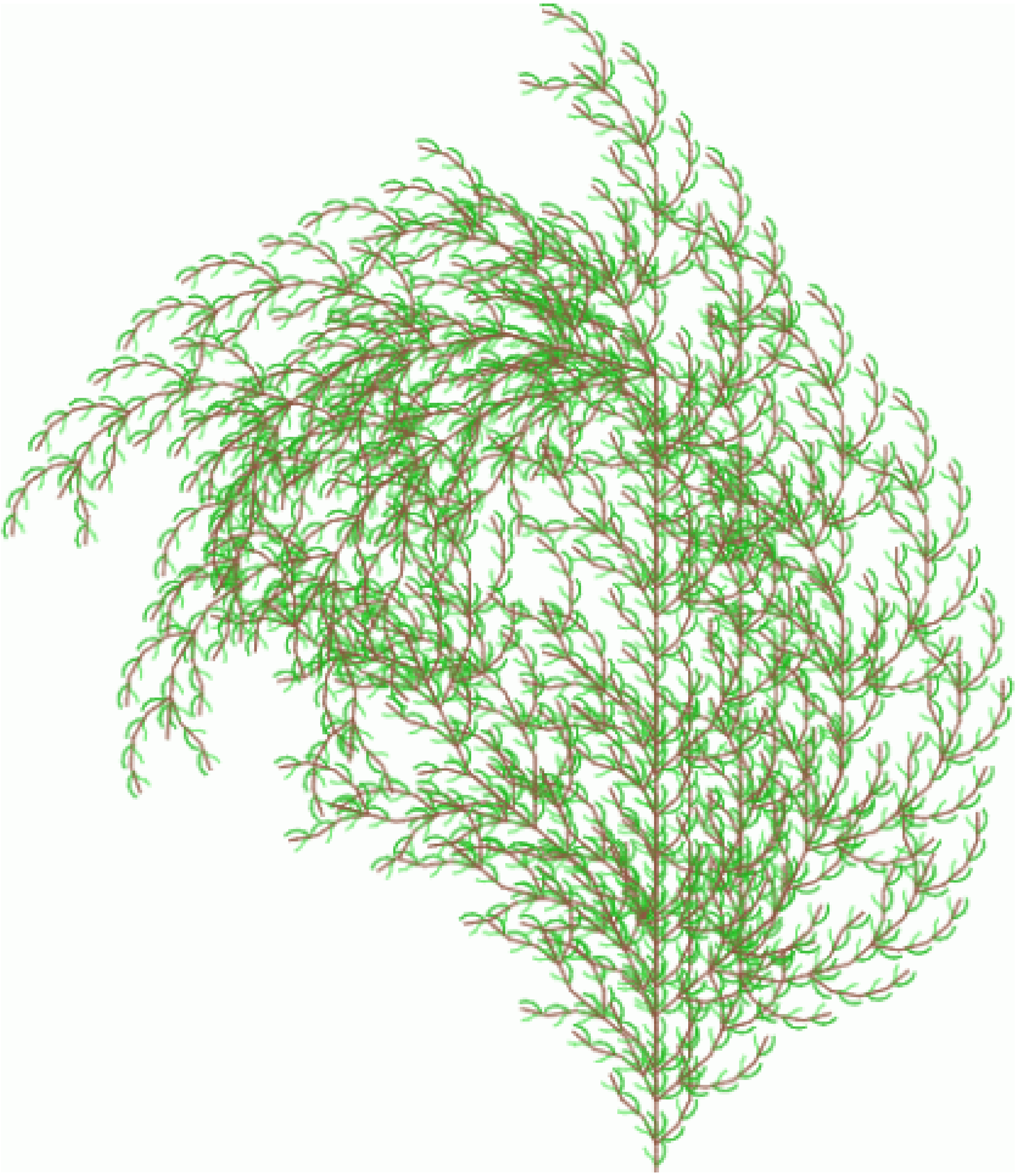

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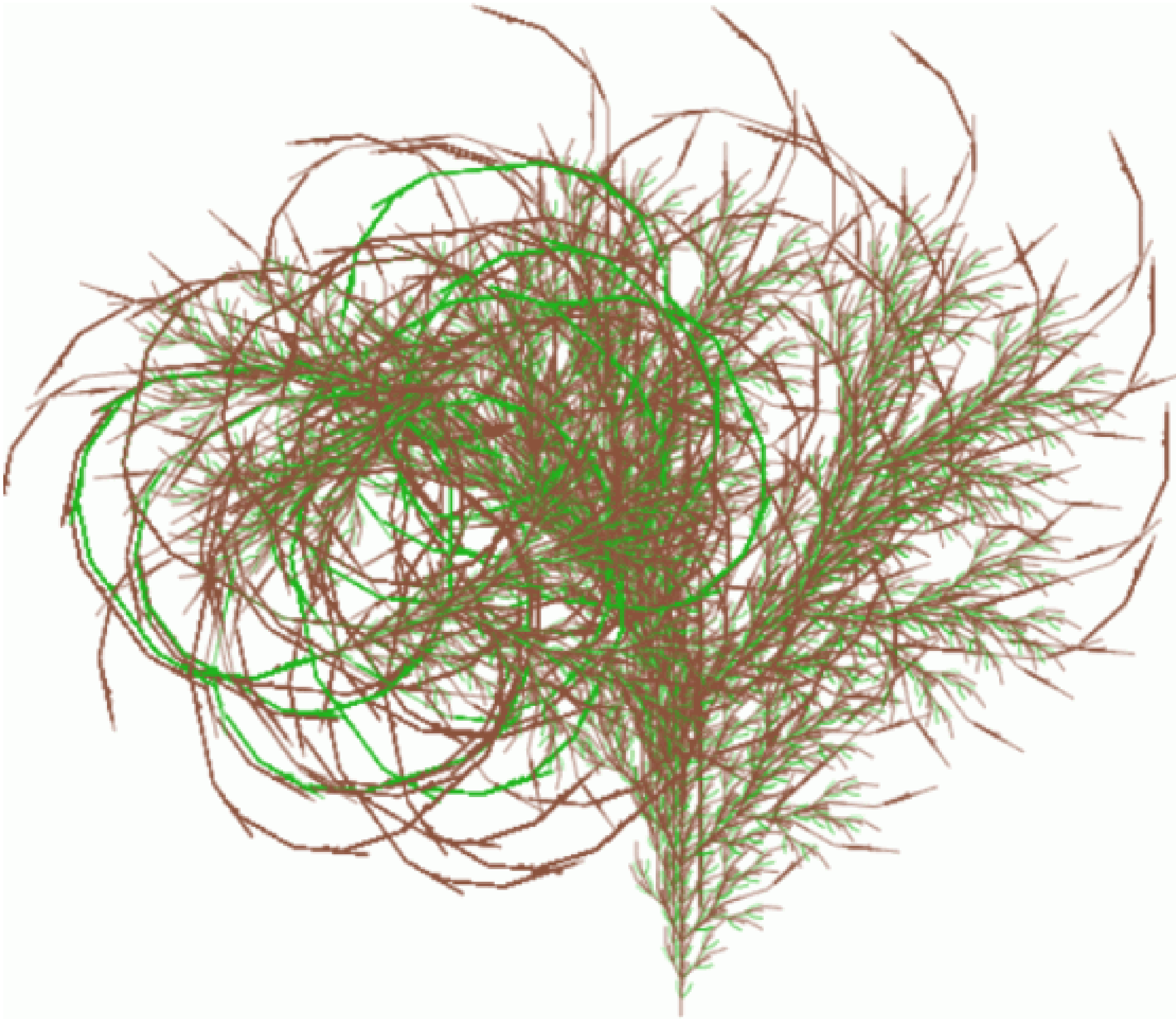

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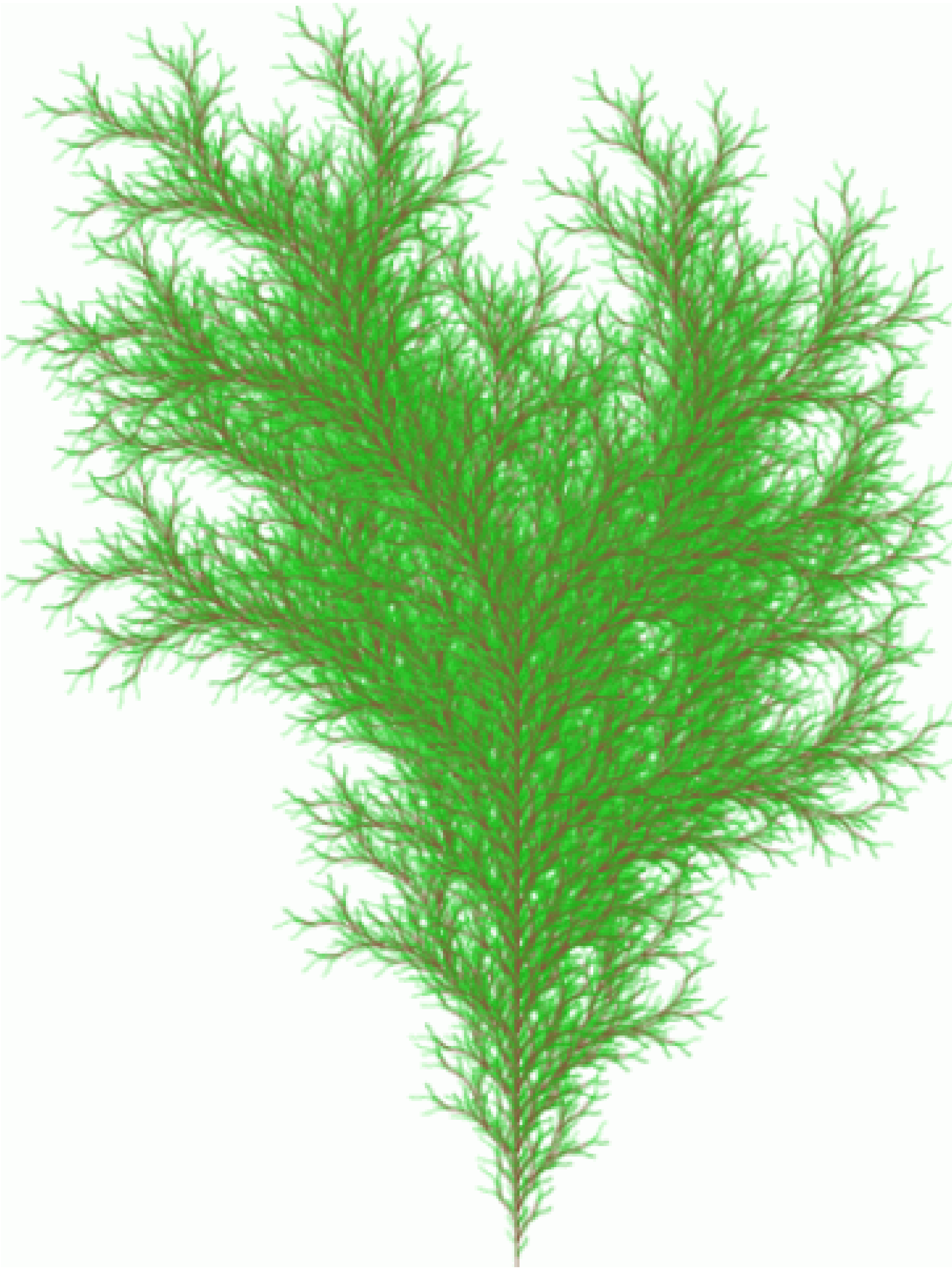

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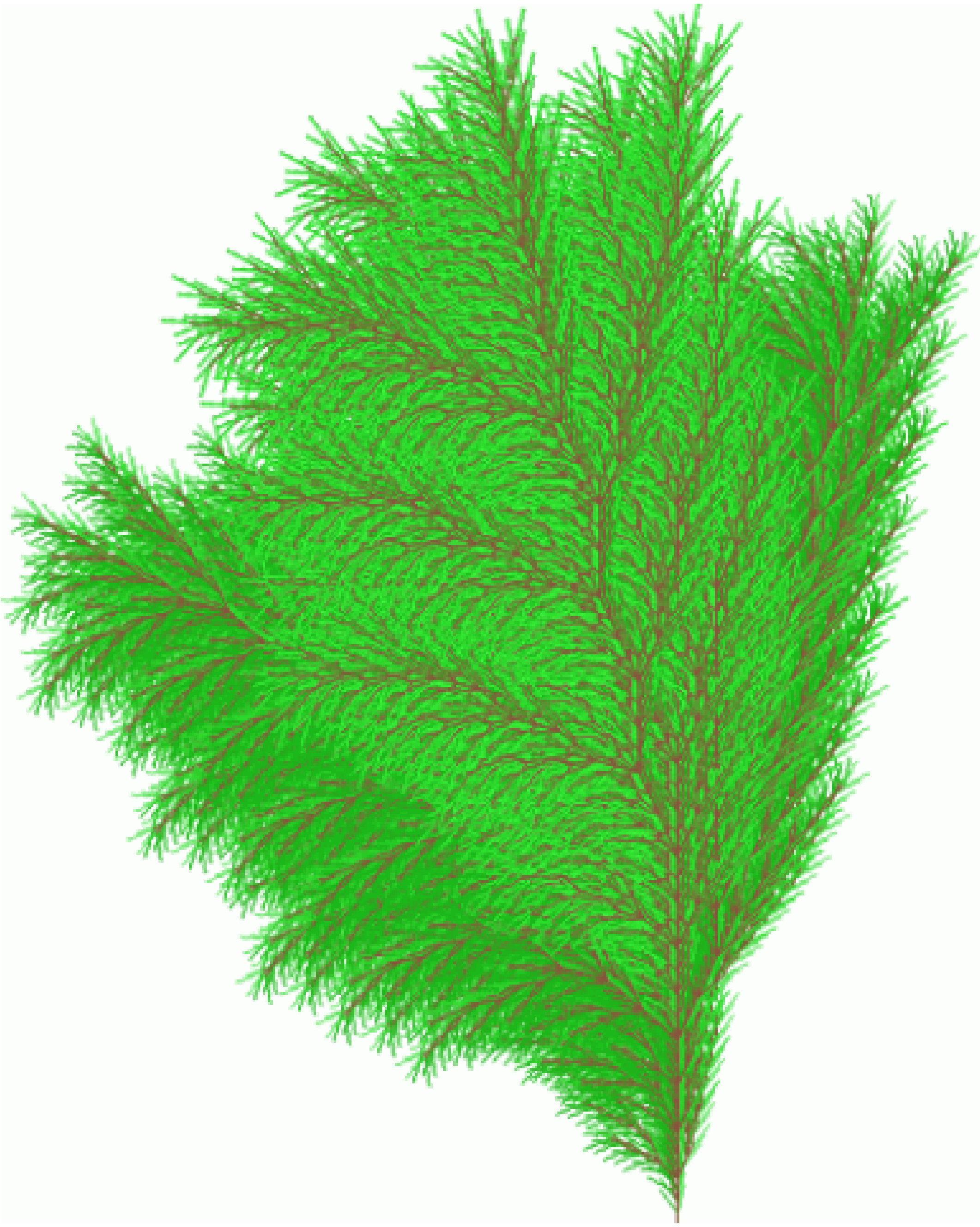

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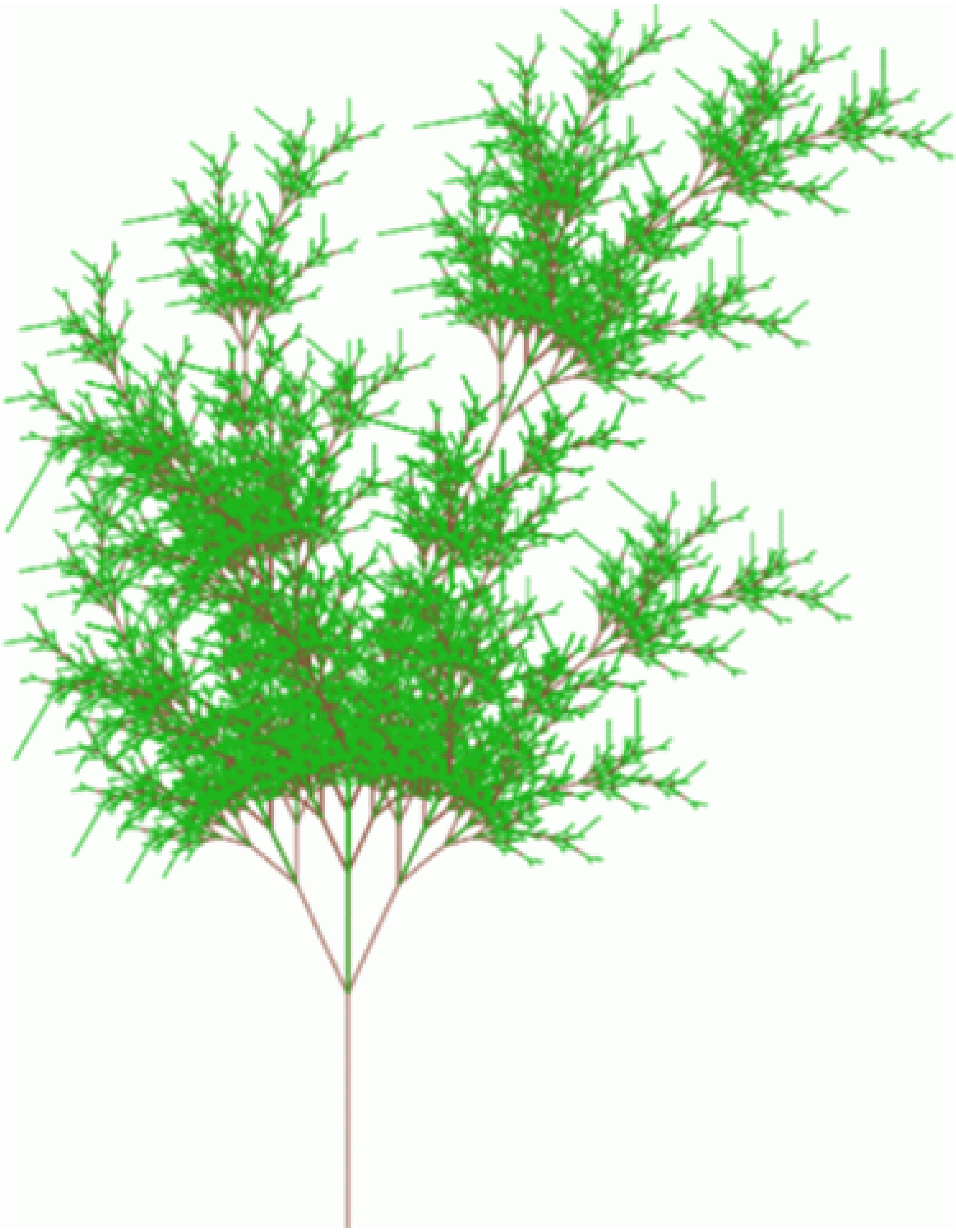

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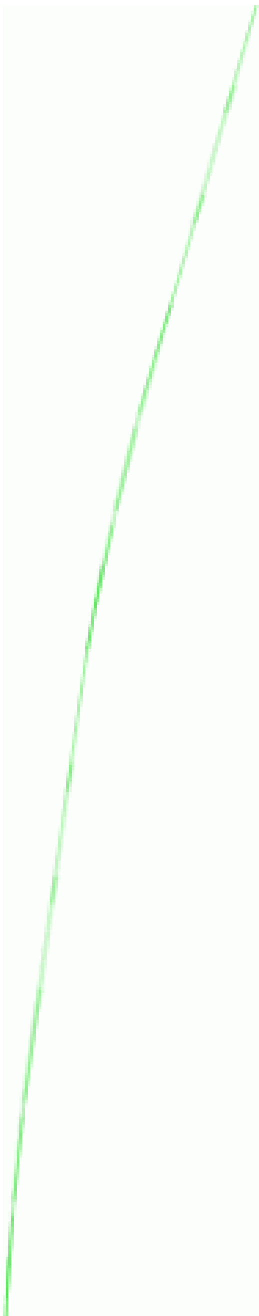

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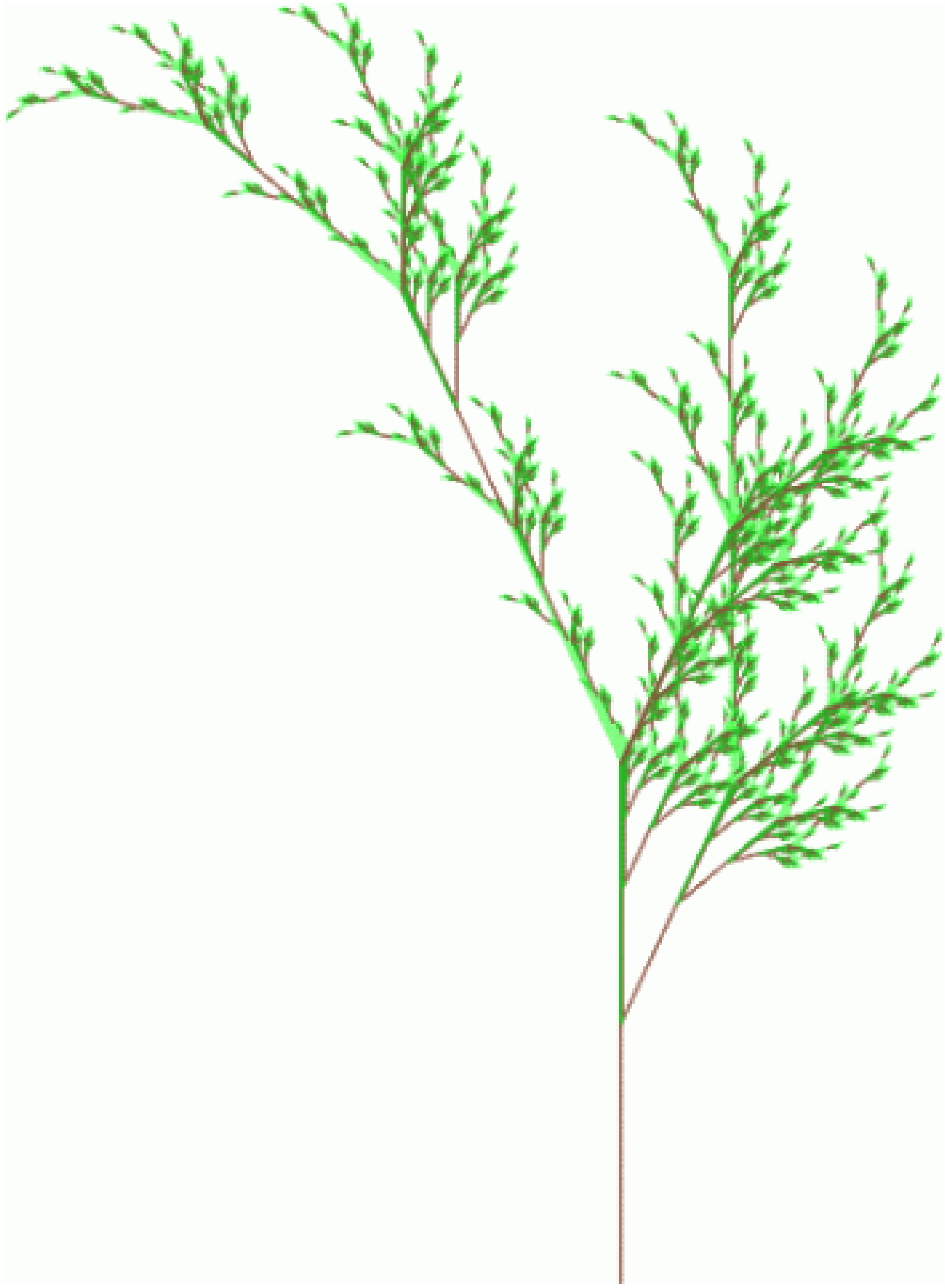

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37 Leaf

37.1 Leaf in general

Definition, functions and features

- Lateral flattened organ of shoot with restricted growth
- Functions:
  - Photosynthesis
  - Respiration
  - Transpiration

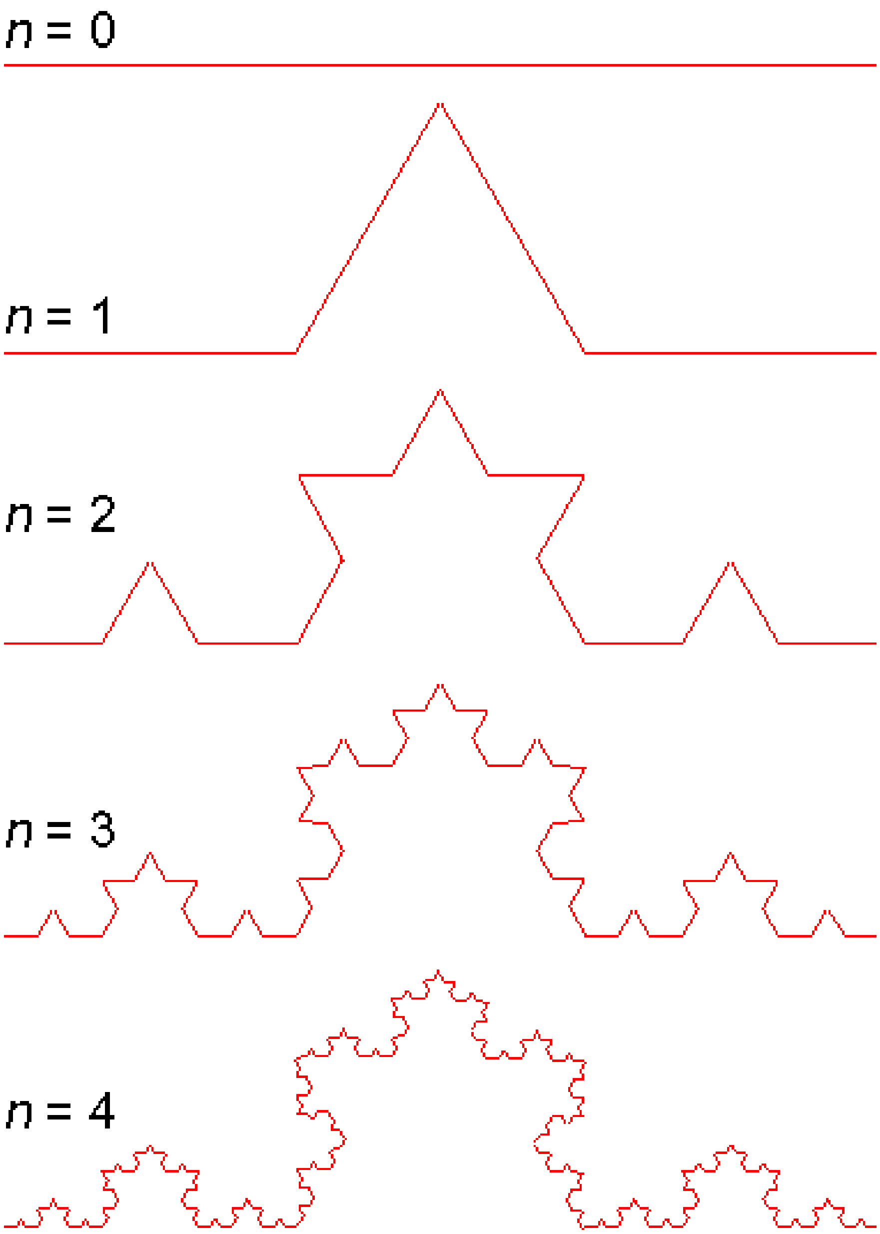
  - Synthesis of secondary chemicals

- Features:
  - Have bud in the axil (remember compound leaves)
  - Do not grow by apex
  - Do not produce new leaves
  - Have hierarchical (fractal) morphology

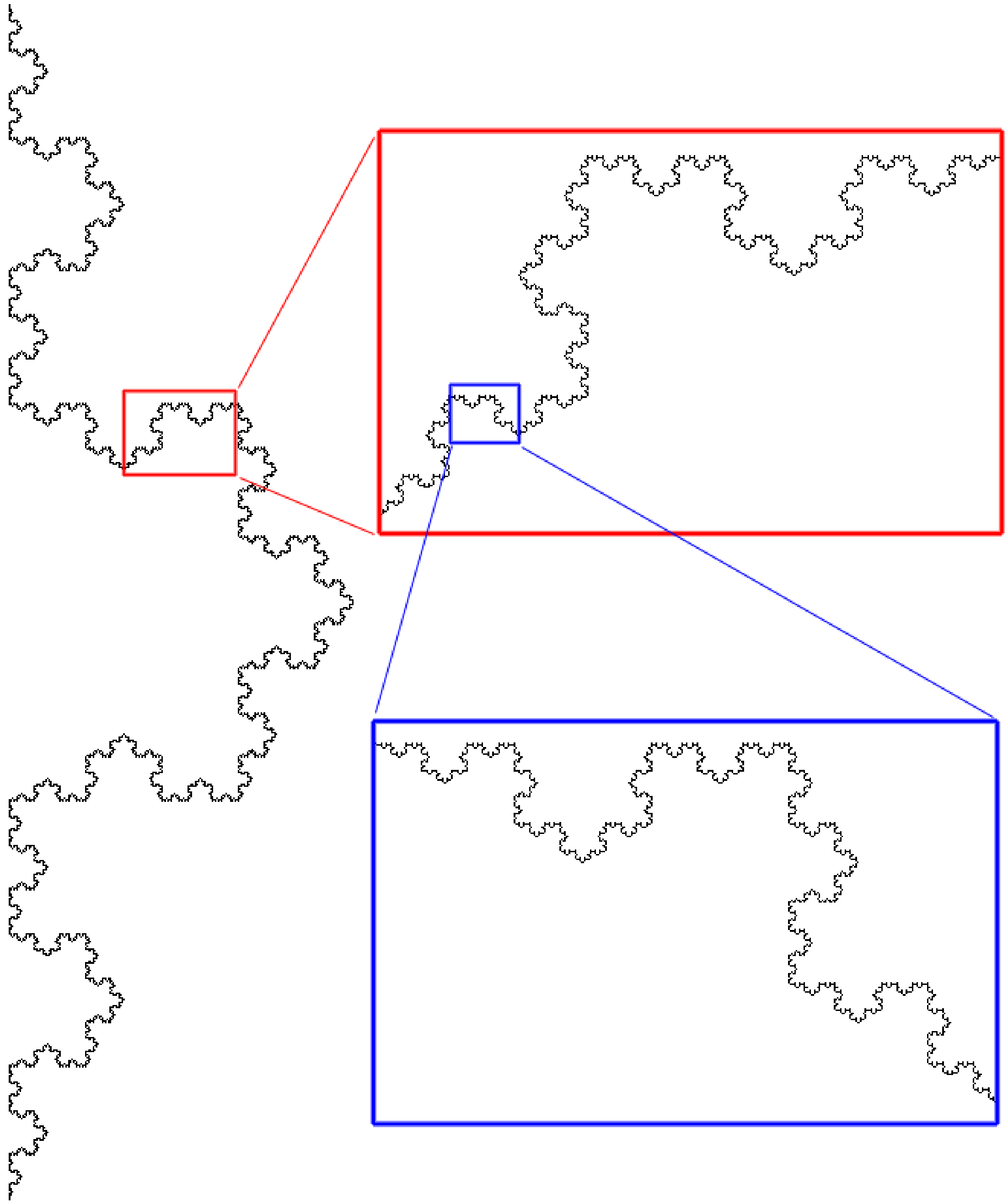
37.2 Leaf morphology

Hierarchy

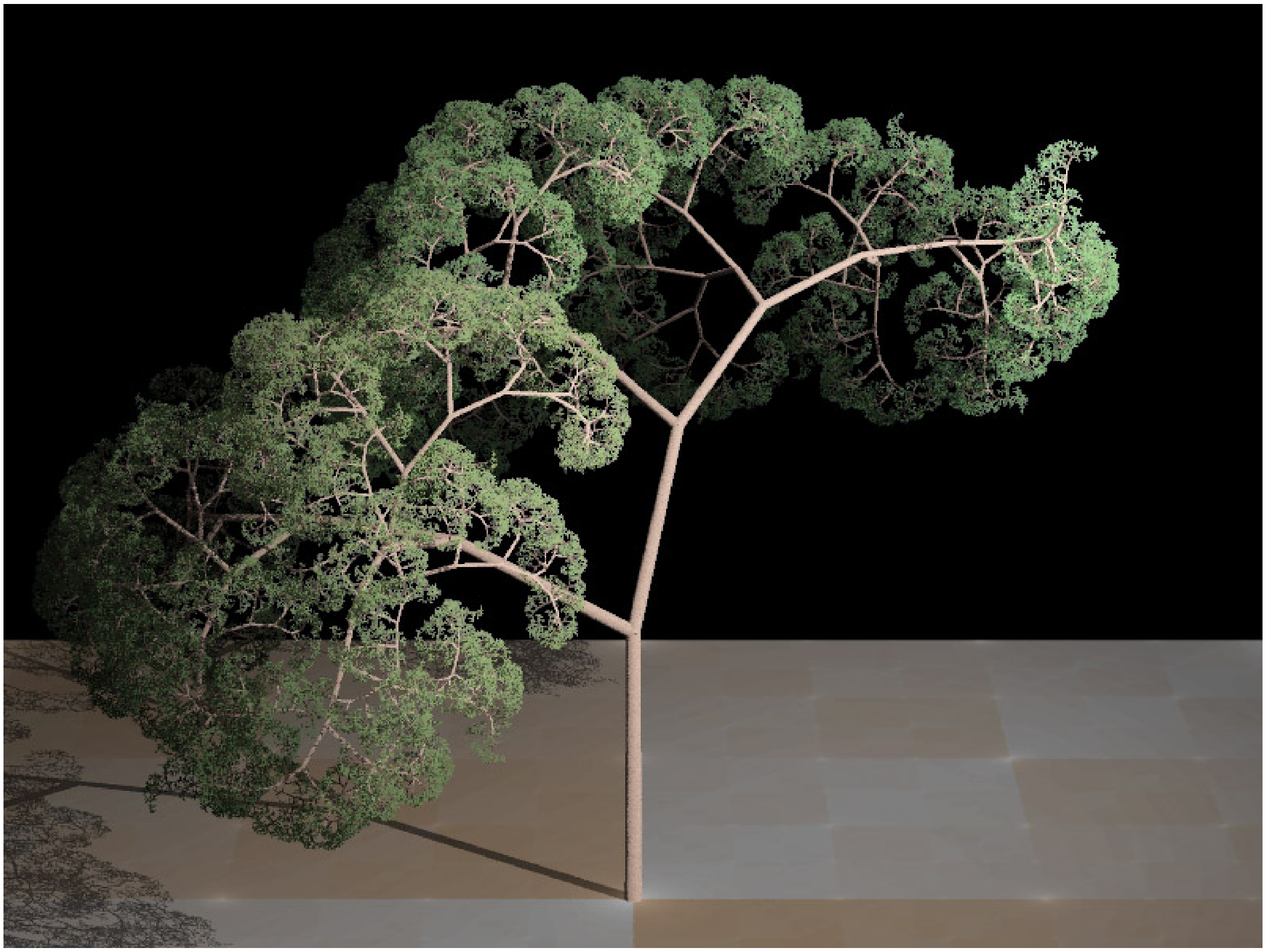
Fractals are hierarchical



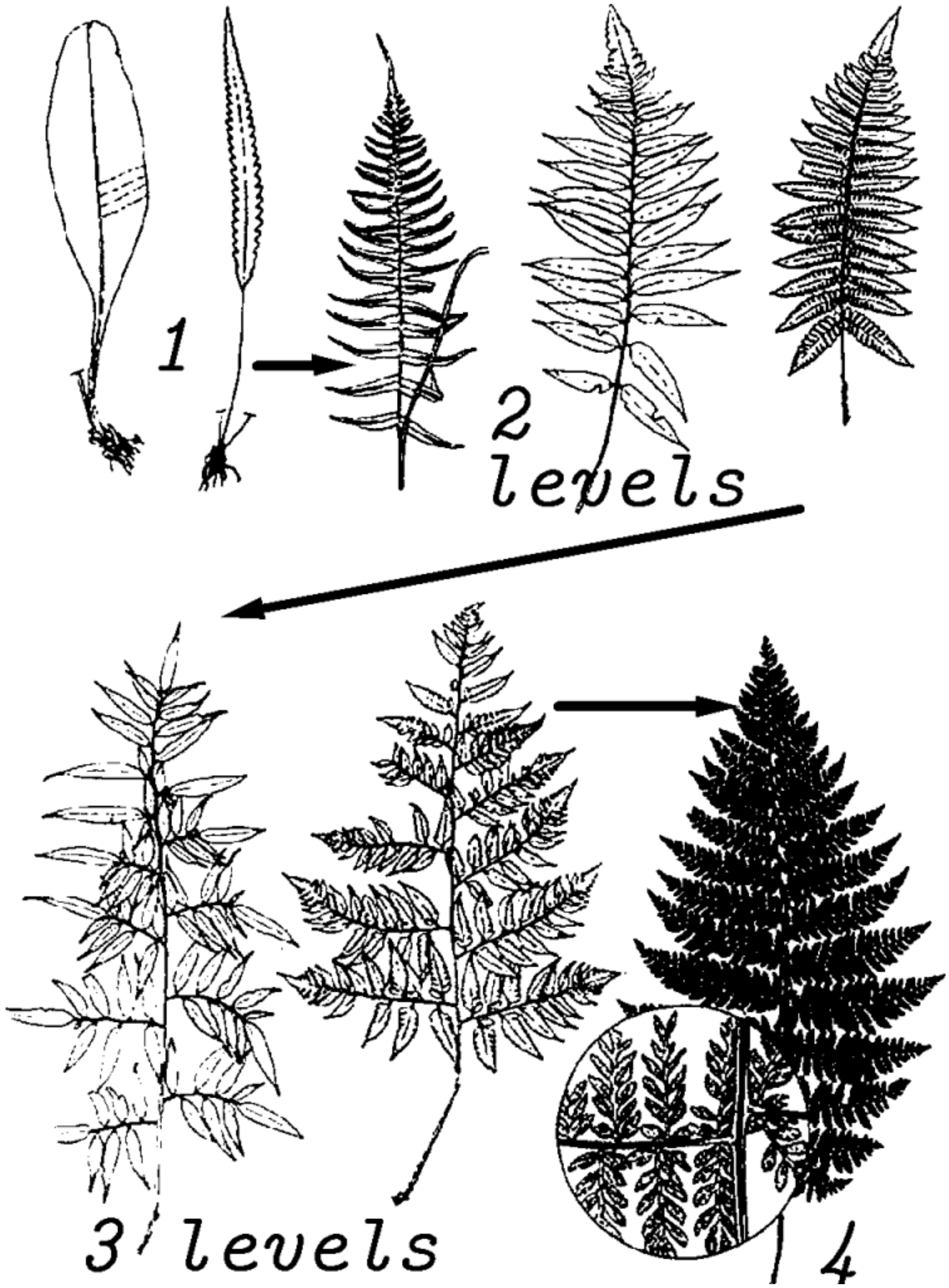
Fractals are self-similar



Fractals could be just like plants



And leaves could be just like fractals, with levels



Types of leaf characters

- General: applicable only to the whole leaf
- Terminal: applicable only to the terminals (e.g., terminal leaflets)
- Repetitive: repeating on each level of hierarchy

Hierarchy in leaf morphology

- **General** and **terminal** characters do not depend on hierarchy
- **Repetitive** characters may be different on each step of hierarchy

- Therefore, leaf description should state that "on first level of hierarchy, the shape is ..., on the second level, the shape is ..."
- It is possible that each level has different repetitive characters

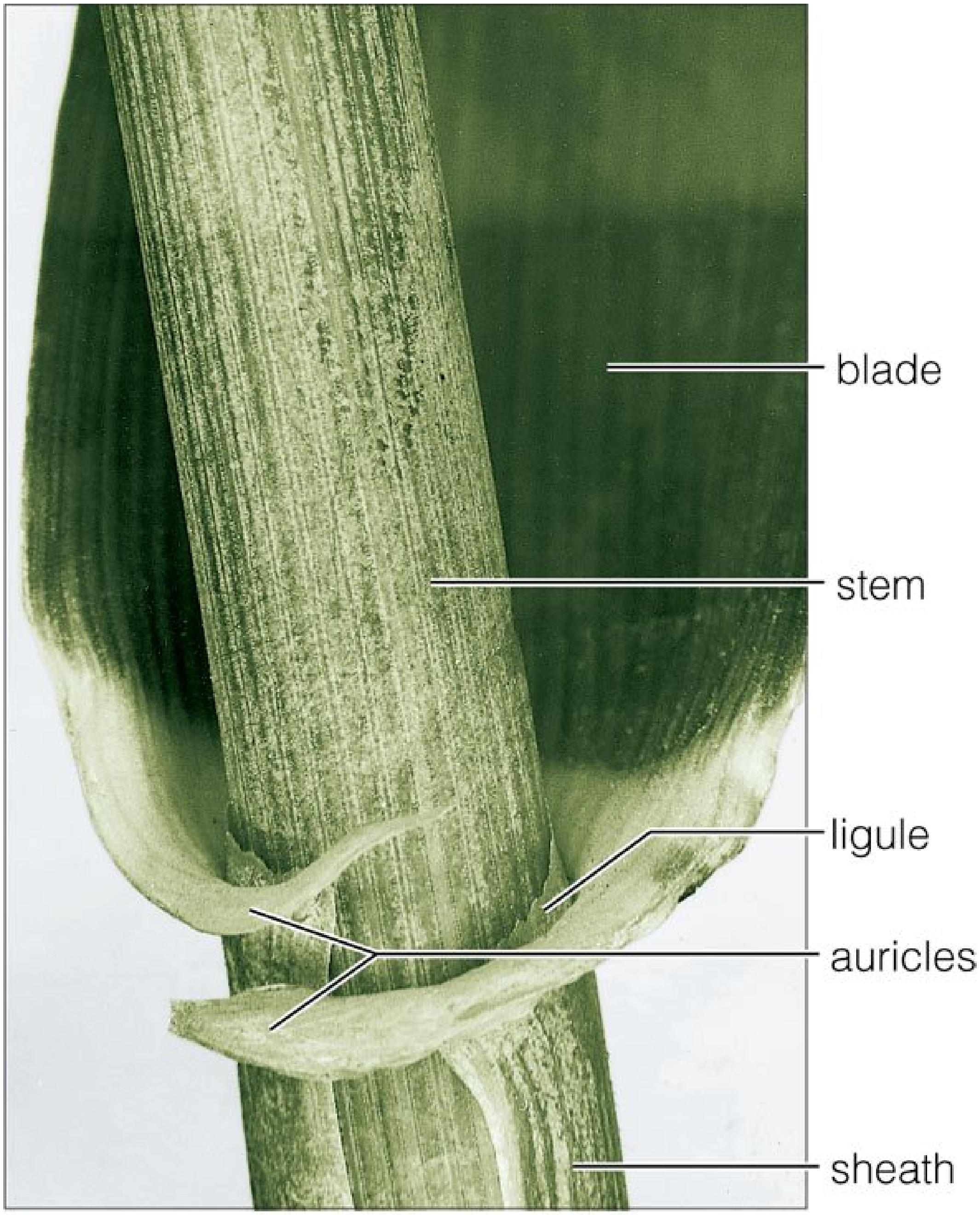
37.3 General characters

General characters

- General characters apply to the whole leaf
- Stipules (present or not, how many etc.)
- Other leaf base organs (sheath, ocrea, ligules etc.)

Stipules

Leaf base



37.4 Repetitive characters

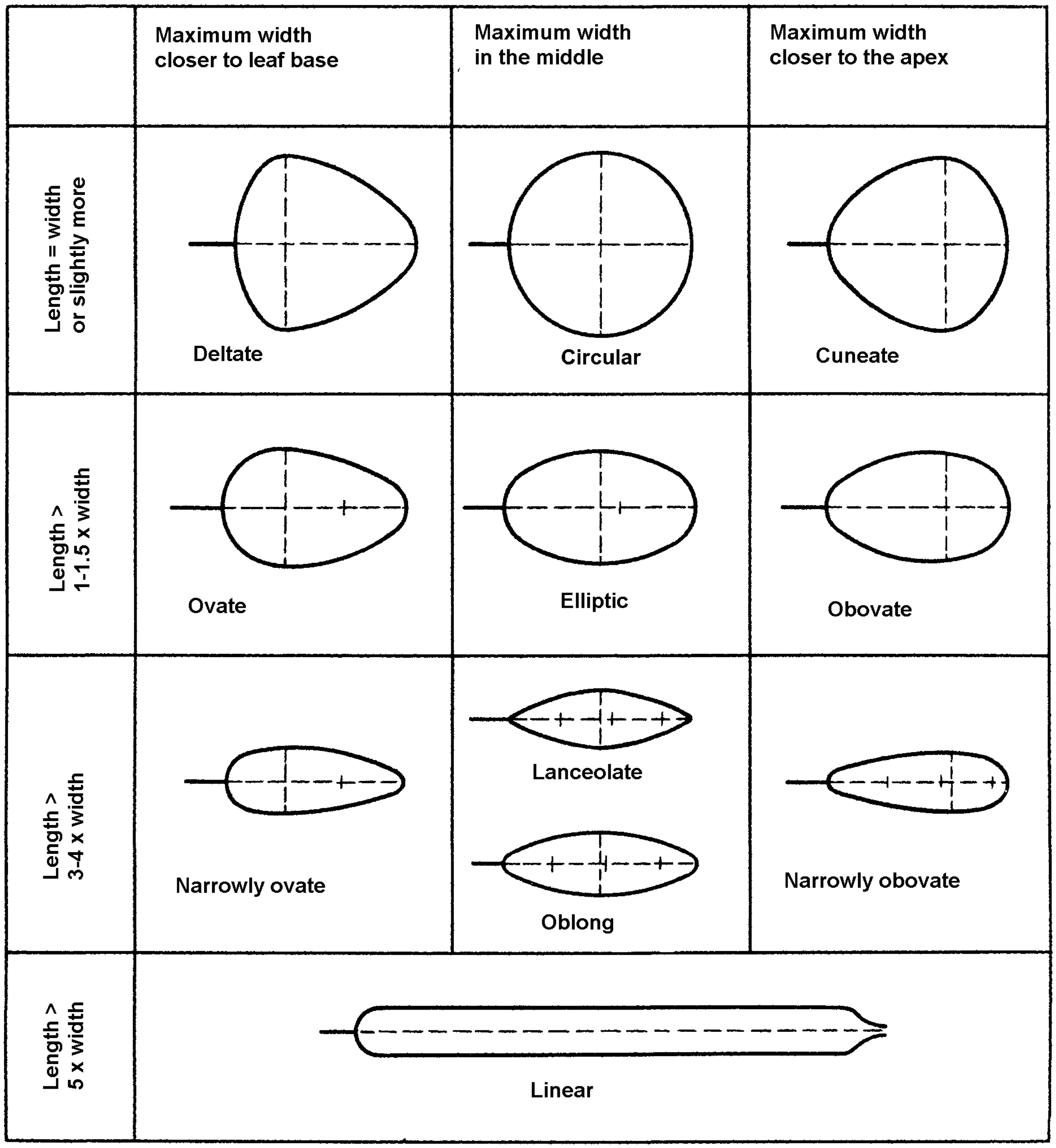
Repetitive characters

Repetitive characters are the same on each level of leaf hierarchy:

- Shape
- Dissection
- Petiole (stalked/non-stalked etc.)

Repetitive characters of same type may combine

Shape



37.5 Repetitive characters

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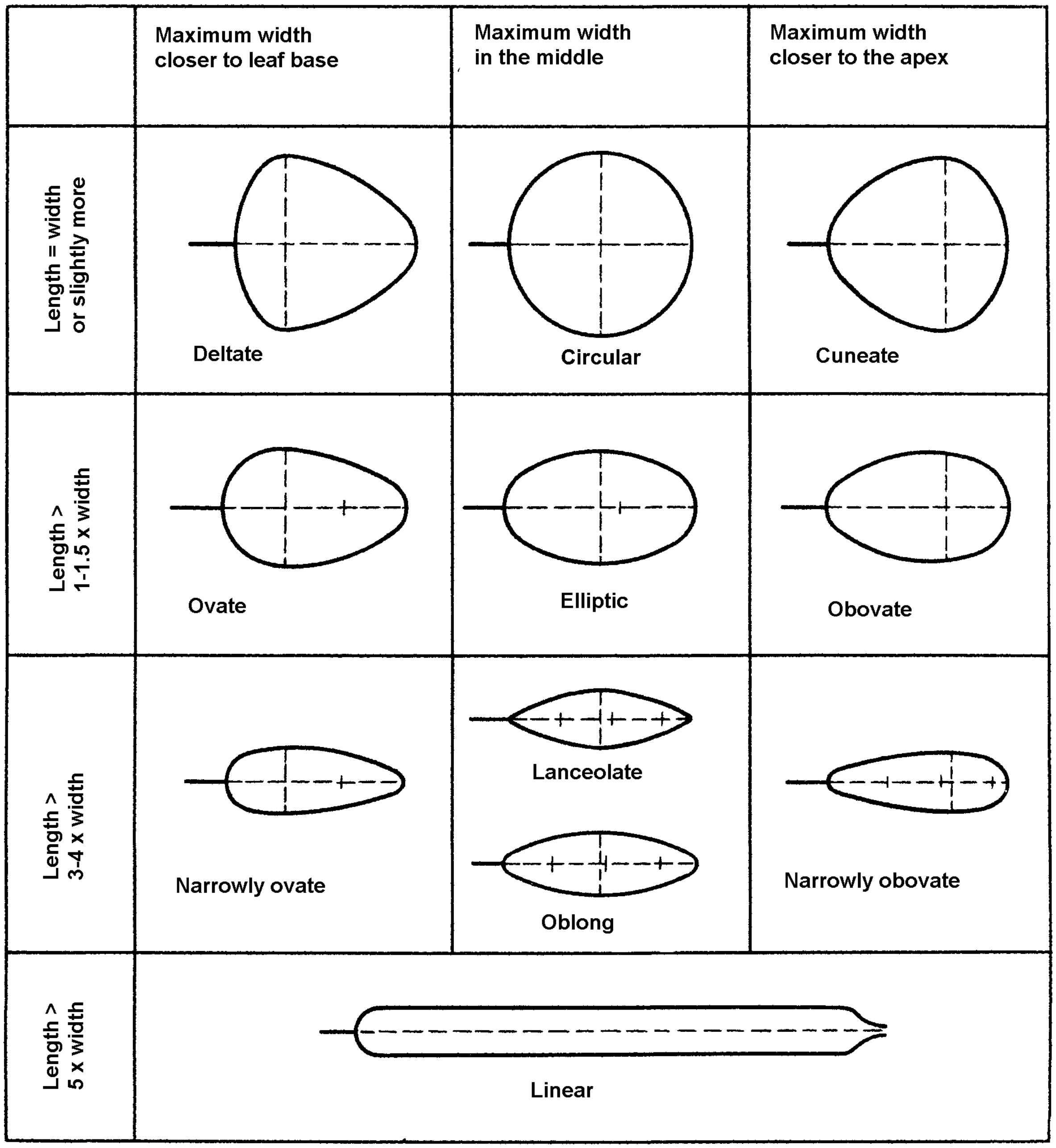
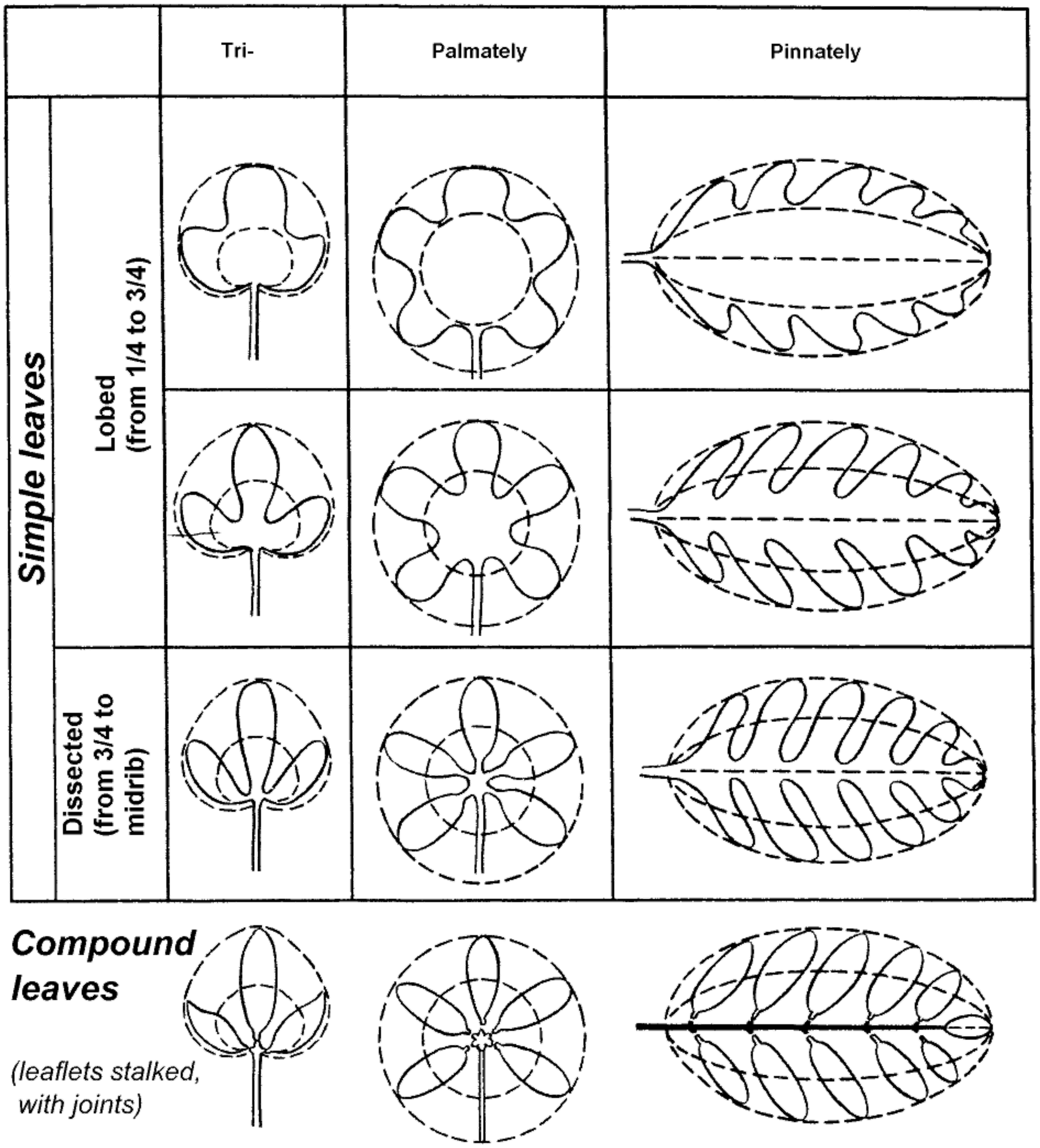


Dissection



37.6 Terminal characters

Terminal characters

Terminal (leaflet) characters are applicable only to terminal parts (normally, leaflets) of leaves:

- Form of base
- Form of tip
- Type of margin
- Surface
- Venation

Terminal characters: base of leaf blade

- Rounded
- Truncate (straight)
- Cuneate
- Cordate
- Sagittate

Terminal characters: leaf apex

- Rounded
- Mucronate
- Acute
- Obtuse
- Acuminate
- Retuse

Terminal characters: leaf margin

- Without teeth: smooth
- With teeth
  - Dentate
  - Serrate
  - Crenate
- Could be double-dentate, triple-serrate etc.

Terminal characters: leaf venation

Lateral veins \ Main vein	No	One	Several
No	Apodromous	Hypho-	Acro-
Several	Dichotomous	Ptero-	Actino-

Plan of leaf description

A. General characters (leaf as a whole):

   (a) stipules (present / absent, deciduous / not);
   (b) base (sheath / no sheath, ligule / no ligule, auricles / no auricles)

B. First level of hierarchy: repetitive characters:

   (a) symmetry (symmetrical / asymmetrical);
   (b) shape;
   (c) dissection;
   (d) petiole (length)

C. Second level of hierarchy

D. Third level of hierarchy and so on

E. Terminal characters (leaflets):

   (a) base [of leaf blade] (rounded, truncate, cuneate, cordate, sagittate);
   (b) apex (rounded, mucronate, acute, obtuse, acuminate, retuse);
   (c) margin (whole, dentate, serrate, crenate; degree of order);
   (d) surface (color, hairs etc.);
   (e) venation (apo-, hypho-, acro-, ptero-, actinodromous)

Summary

- Leaves have **general**, **repetitive** and **terminal** characters

Quiz question (... points)

...

For Further Reading

References

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

Outline

38 Leaf

38.1 Leaf morphology

Plan of leaf description

A. General characters (leaf as a whole):

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   (c) margin (whole, dentate, serrate, crenate; degree of order);
   (d) surface (color, hairs etc.);
   (e) venation (apo-, hypho-, acro-, ptero-, actinodromous)

38.2 Leaves in nature

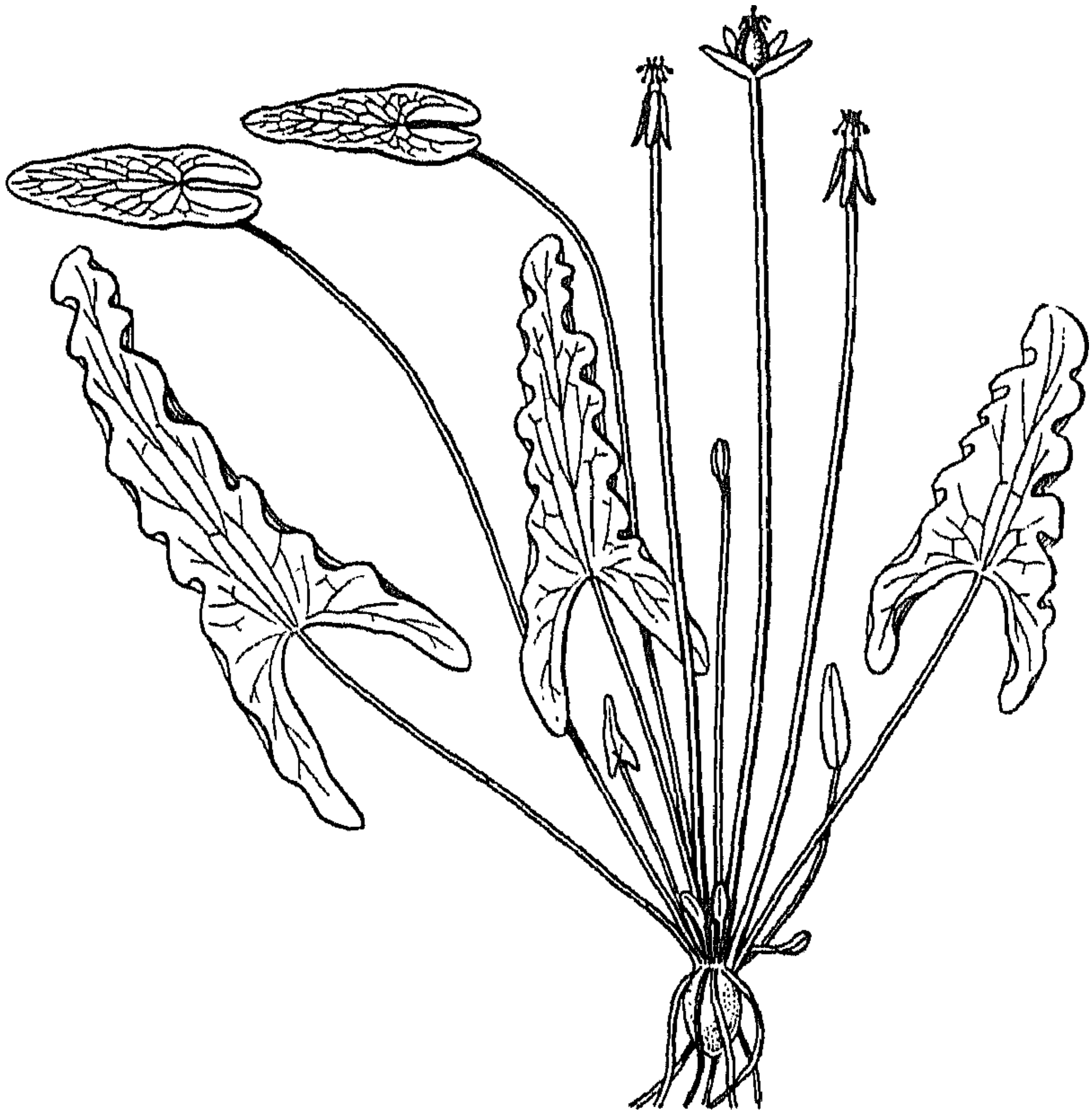
Heterophylly

- Juvenile and adult leaves
- Water and air leaves
- Sun leaves and shade leaves

Juvenile leaves of *Juniperus* sp.

Juvenile leaves of *Eucalyptus* sp.

Submerged and floated leaves of *Ondinea*



Leaf mosaic

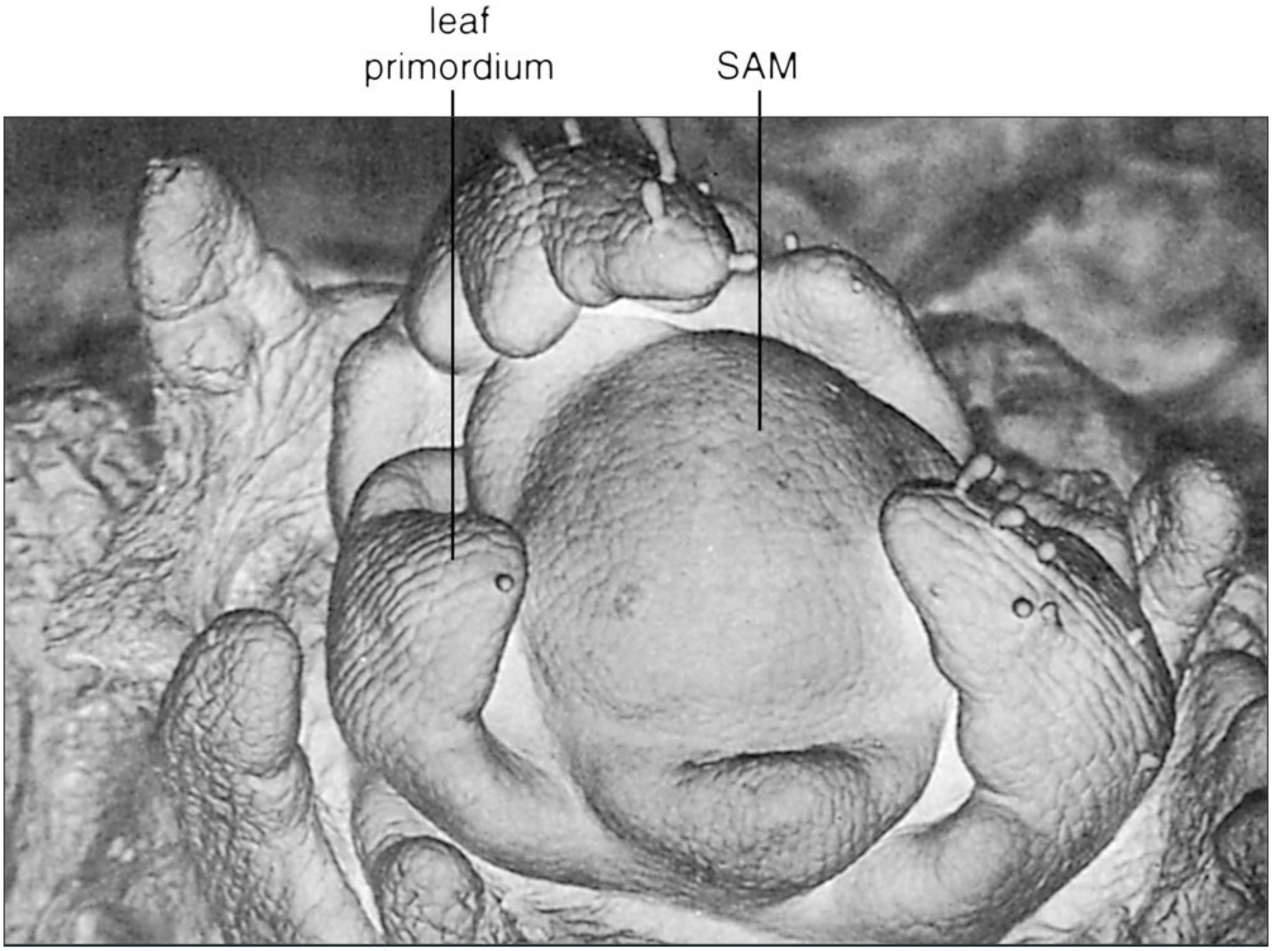
- Distribution of leaves of plants in a single plane, usually perpendicular to light rays
- Provides the least shading of leaves by one another

Leaf mosaic of red maple (*Acer rubrum*)

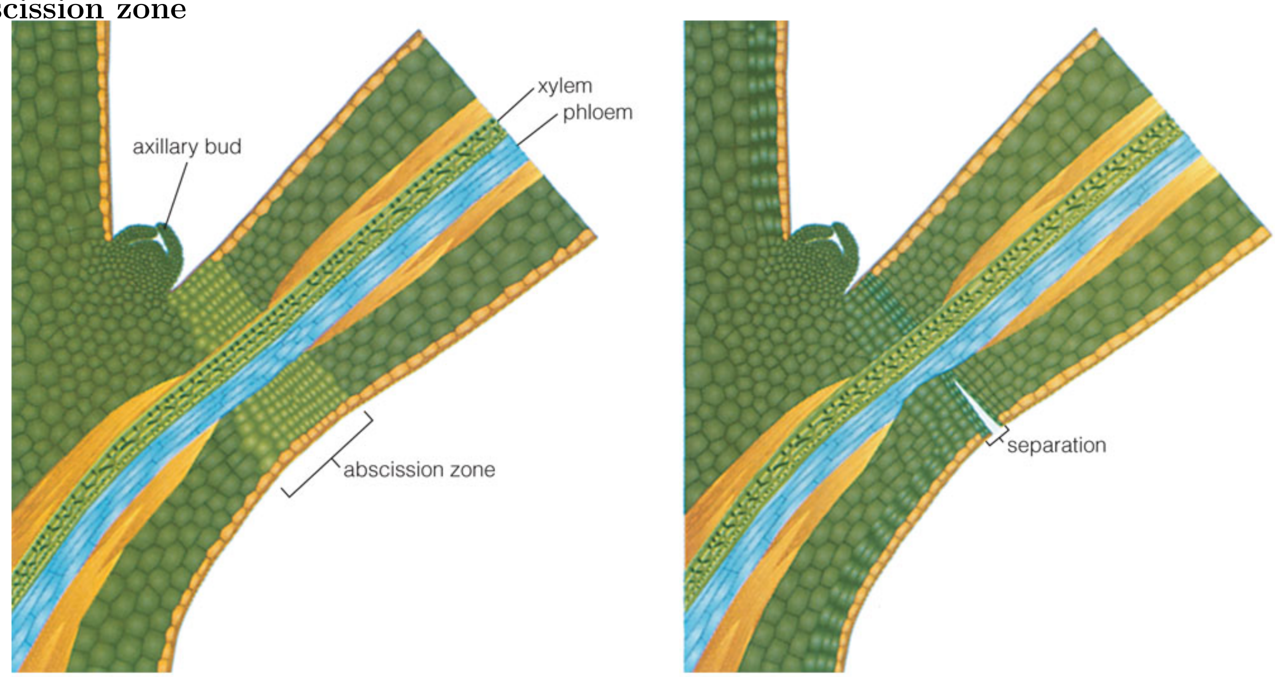
Seasonal life of leaves

- Leaves arise from SAM through leaf primordia
- Old leaves separate from plant in a region called abscission zone

Leaf primordia



Abscission zone



38.3 Modifications of leaf

Goethe's theory of modification

Famous German poet and writer Johann Wolfgang Goethe is also a founder of plant morphology. He invented an idea of "primary plant" ("Urpflanze") where all organs were modifications of one primordial organ.

Leaf modifications

- Spines
- Tendrils
- Succulent leaves
- Traps
- Plantlets

Tendrils of sweet pea (*Lathyrus odoratus*)

Plantlets on the leaf of *Kalanchoe pinnata*

Leaf of Venus flytrap (*Dionaea muscipula*)

Everything is possible when plant needs nitrogen!

Urn leaf of yellow pitcher plant (*Sarracenia flava*)

***Sarracenia flava* on Buttercup Fields, Mississippi**

Prey in the urn

Urn leaf of purple pitcher plant (*Sarracenia purpurea*)

Hairs prevent insects from climbing out of leaf

"Cobra Lily" (*Darlingtonia californica*)

Sticky tape leaf of butterwort (*Pingiucula* sp.)

Leaf margins are slowly rolling

Sticky tape/trap leaf of sundew (*Drosera intermedia*)

Leaves are constantly open and close and finally digest the glued insects

Table of modifications

Function	Stem / shoot	Leaf	Root
Expansion		Plantets	
Storage		Succulent leaves	
Photosynthesis		DEFAULT	
Defense		Spines, scales	
Support		Leaf tendrils	
Interactions		Traps, "sticky tapes", urns	

Summary

- Leaves have **general**, **repetitive** and **terminal** characters
- **Heterophylly** is a co-existence of different types of leaves on the same plant
- **Abscission zone** helps the separation of leaf at the end of season

Quiz question (... points)

For Further Reading

References

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

Outline

39 Questions and answers

39.1 Quiz

Quiz question (2 points)

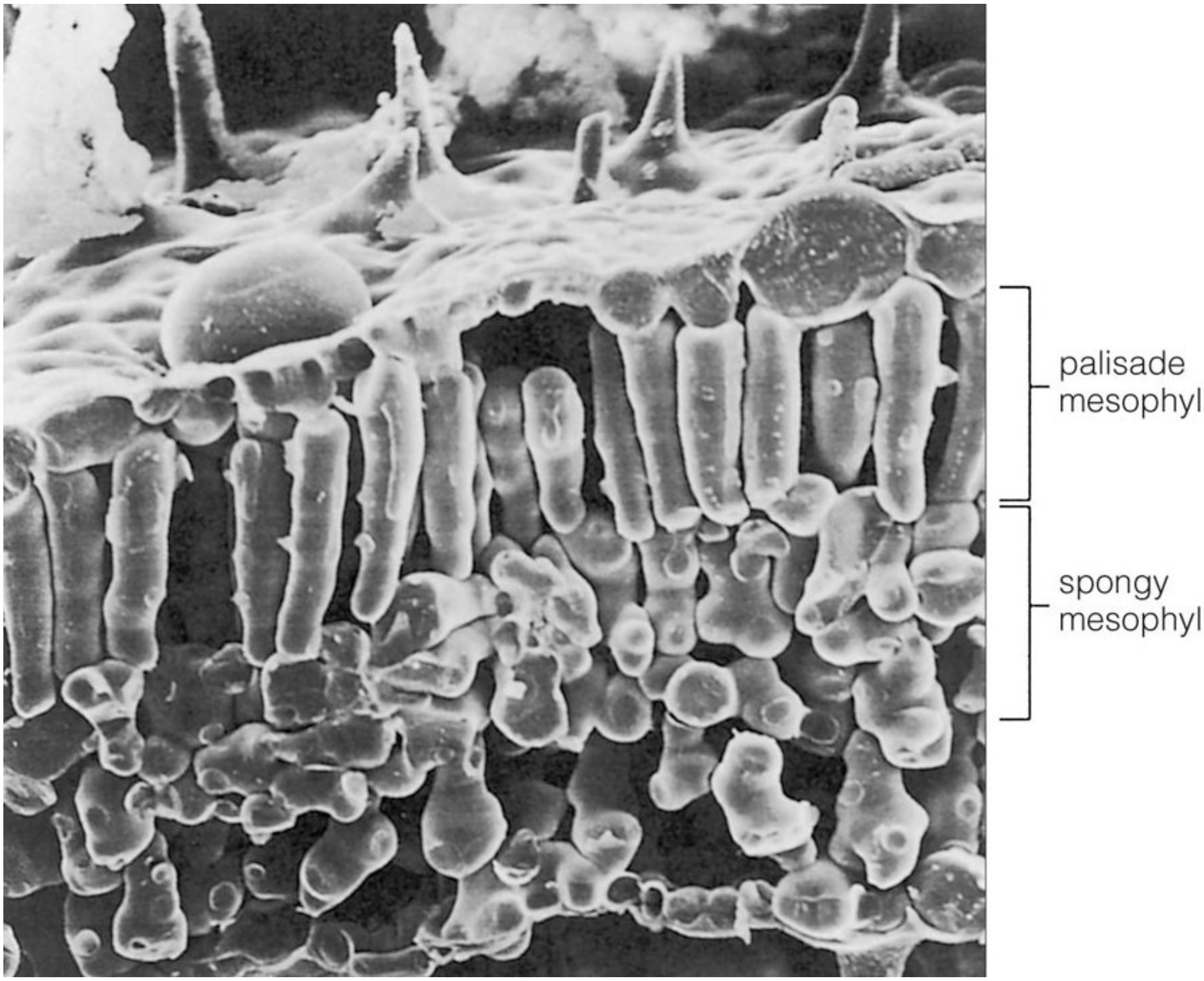
...

- ...

40 Leaf

40.1 Anatomy of leaf

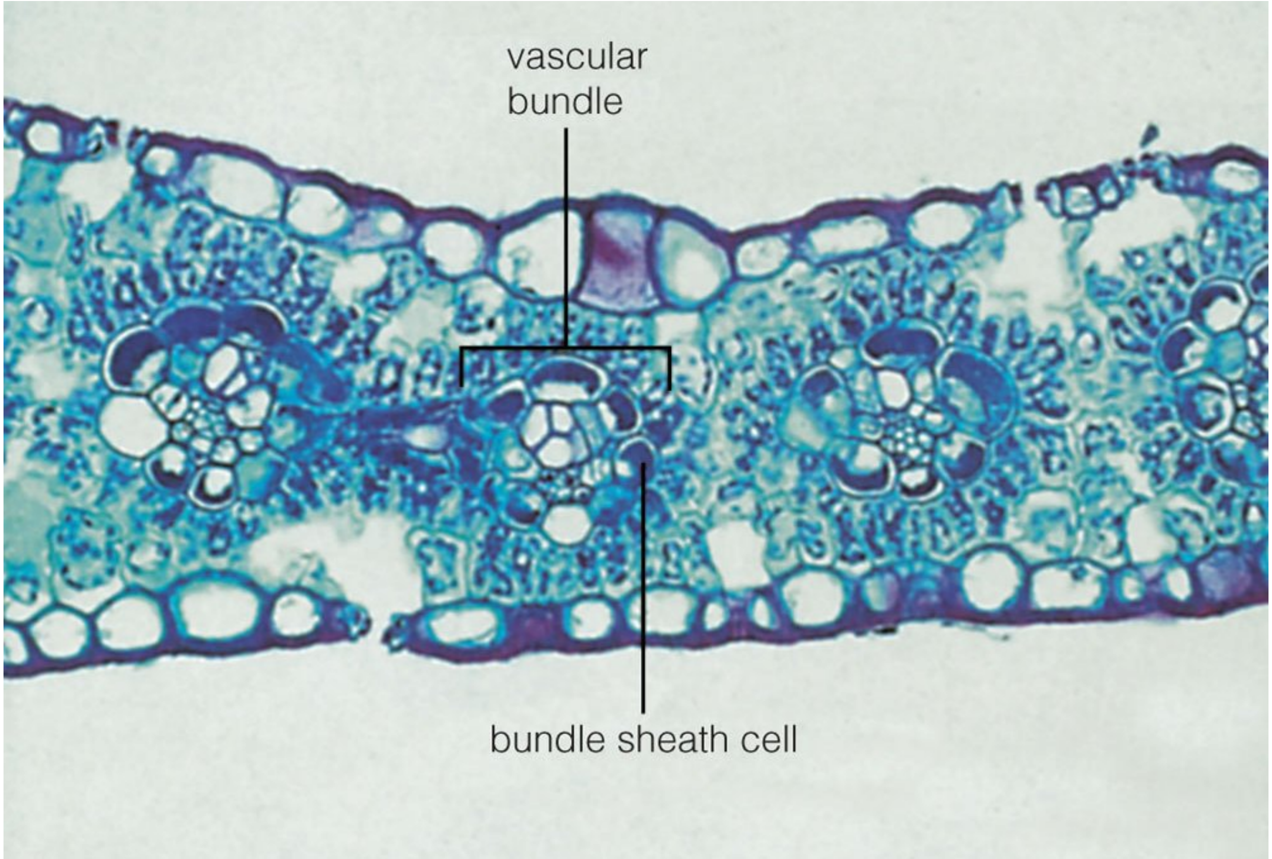
Palisade and spongy cells



Veins/vascular bundles and stomata

- Phloem typically faces downwards, xylem—upwards
- Bundles of C_4-plants have additional bundle sheath cells
- Stomata work with the "bacon principle"

Bundle sheath cells

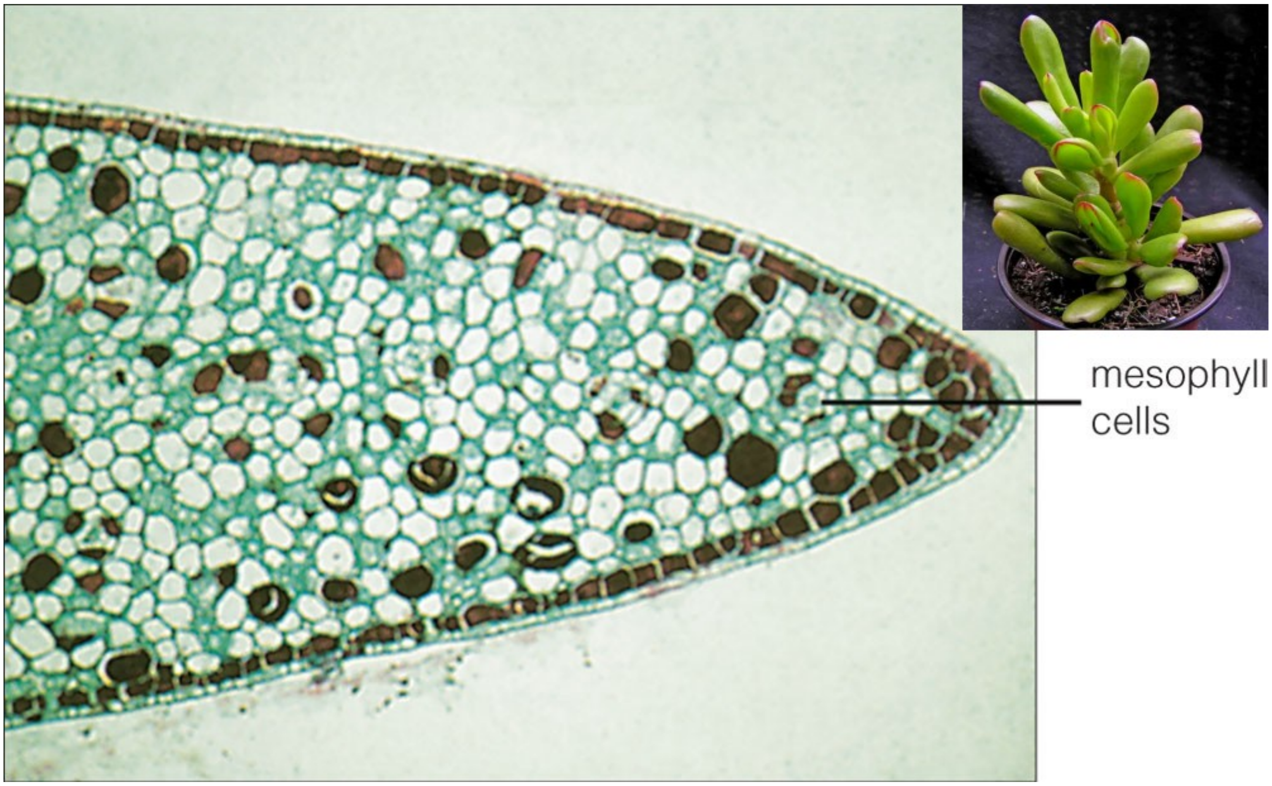


40.2 Ecological adaptations of leaves

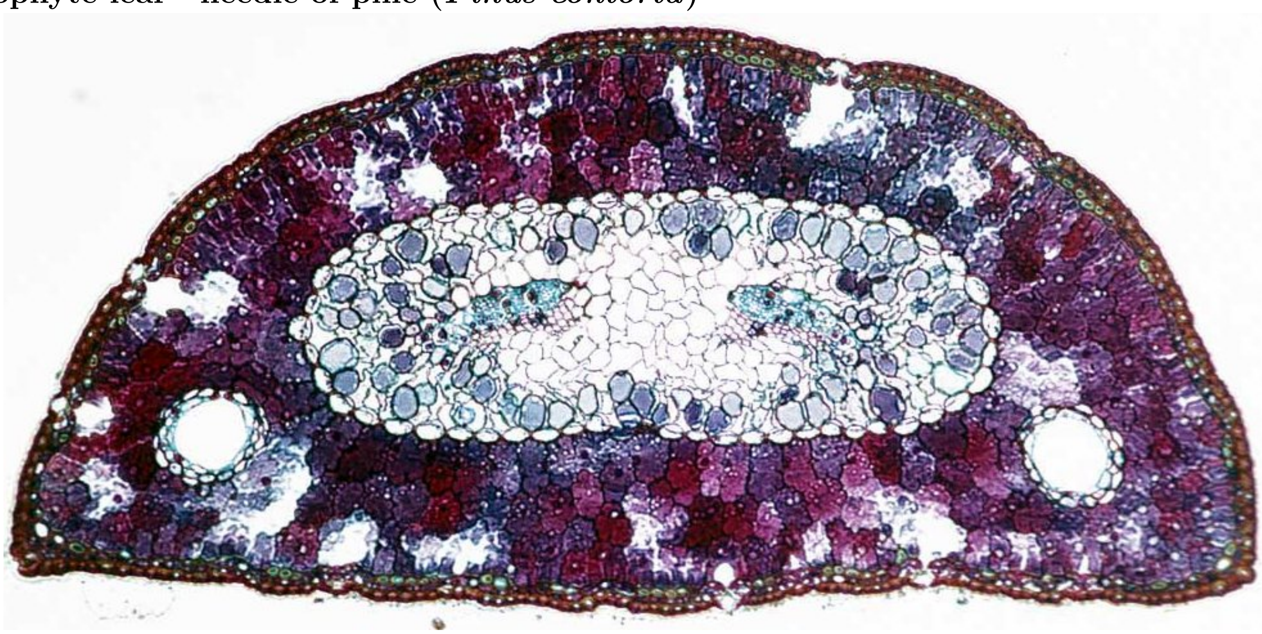
Plants and water

- Xerophytes: sclerophytes and succulents (stem and leaf)
- Mesophytes
- Hygrophytes
- Hydrophytes

Leaf succulent (*Crassula argentea*)



Xerophyte leaf—needle of pine (*Pinus contorta*)



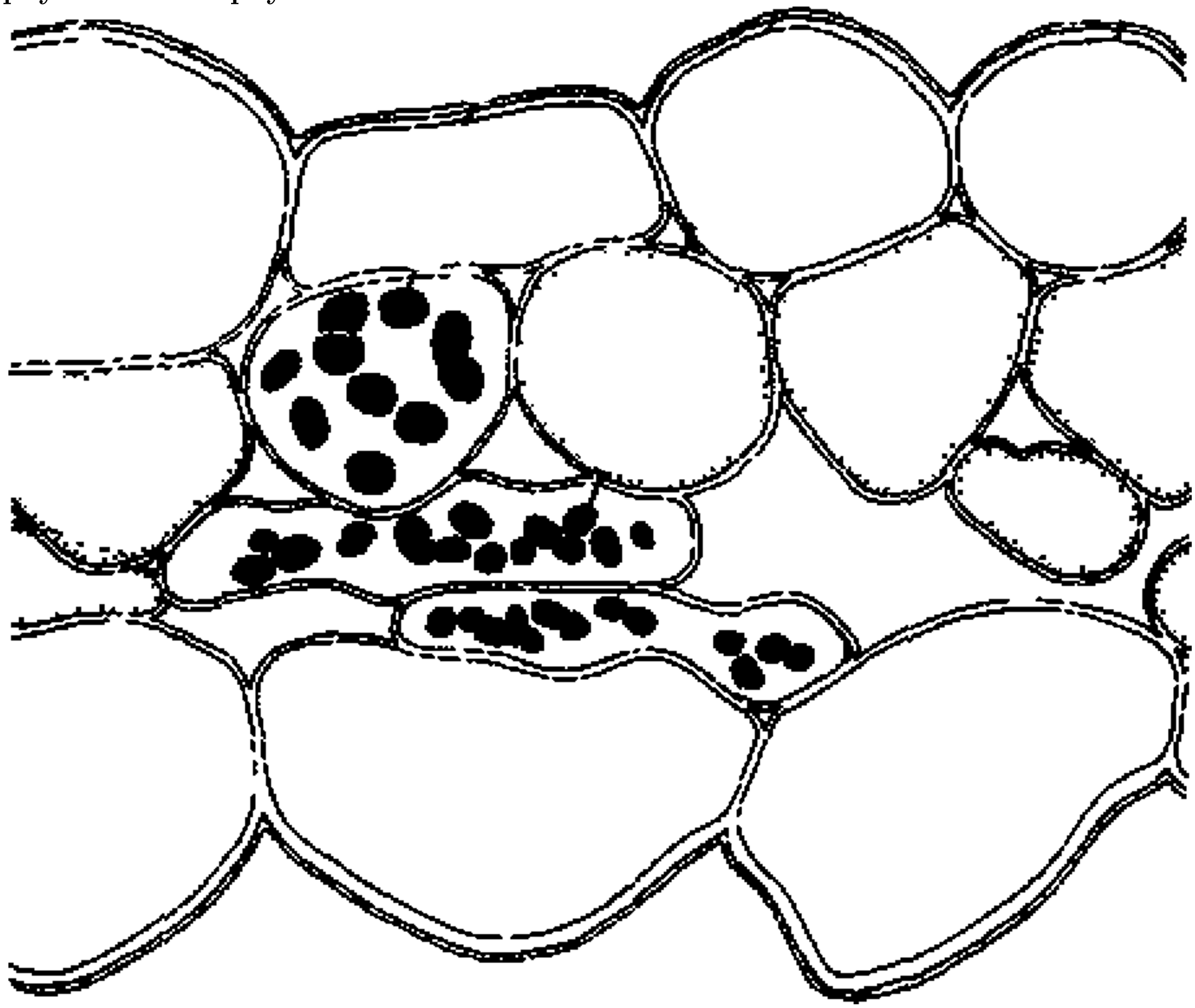
41 Leaf

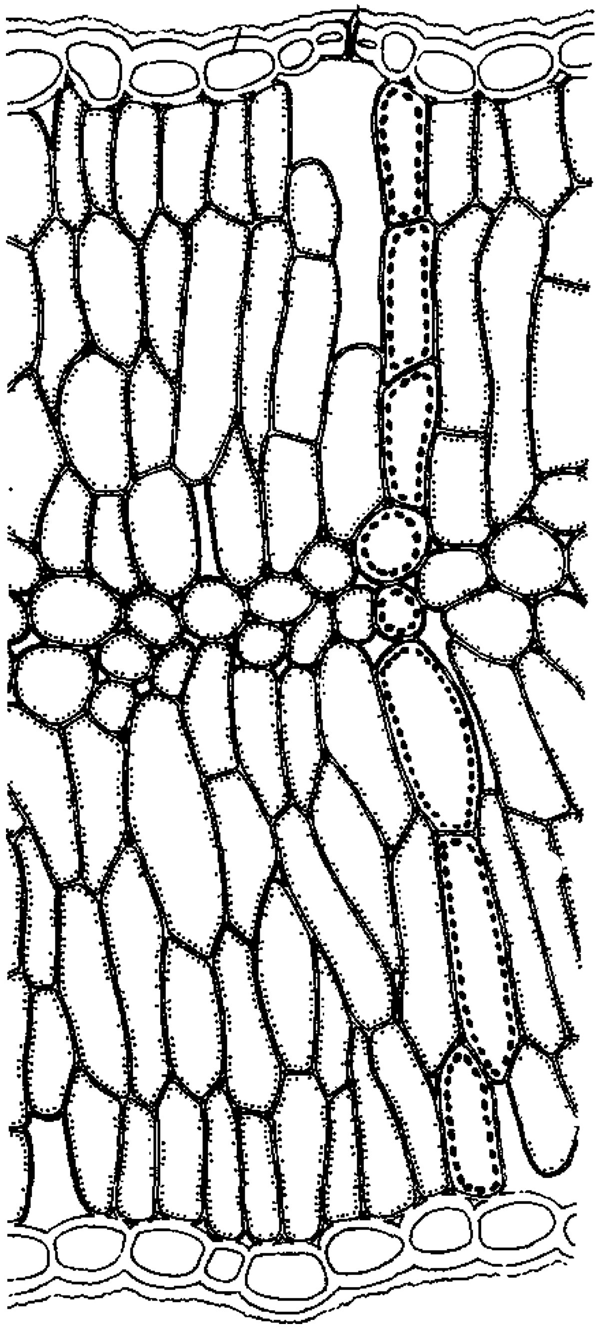
41.1 Ecological adaptations of leaves

Plants and light

- Sciophytes
- Heliophytes

Sciophyte and heliophyte





Oxalis acetosella and *Sylphium laciniatum*

Leaves and soil

- Halophytes (accumulate, excrete or avoid NaCl)
- Nitrate halophytes (grow on soils rich of $NaNO_3$)
- Oxylophytes (grow on acidic soils)
- Calciphytes (grow on chalk soils rich of $CaCO_3$)

Leaf of salt-accumulating halophyte

Atriplex prostrata

Leaves and substrate

- Psammophytes (grow on sand)
- Petrophytes (grow on rocks)
- Rheophytes (grow in fast springs)

Rheophyte

Macarenia clavigera from Venezuela

River with rheophytes

They are flowering, too

Podostemum ceratophyllum (may be found even in ND!)

Podostemum in North Carolina

Leaves and metabolism

- Mycoparasites
- Hemiparasites
- Phytoparasites (root and stem)

Mycoparasite

Triuris hyalina from South America

Hemiparasite

Krameria parvifolia from southern Texas

Root parasite

Hydnora africana from South Africa

Stem parasite

Cuscuta europaea from Germany

For Further Reading

References

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

Outline

42 Stem and shoot

42.1 Plant body

Structure of plant body: the first glance

- Shoot system (aboveground part: stems, leaves, buds, flowers, fruit)
- Root system (below-ground part: main roots and branches)
- Exceptions:
  - Some mosses and even ferns have only shoot system
  - Liverworts and hornworts frequently have only leaf-like thallus

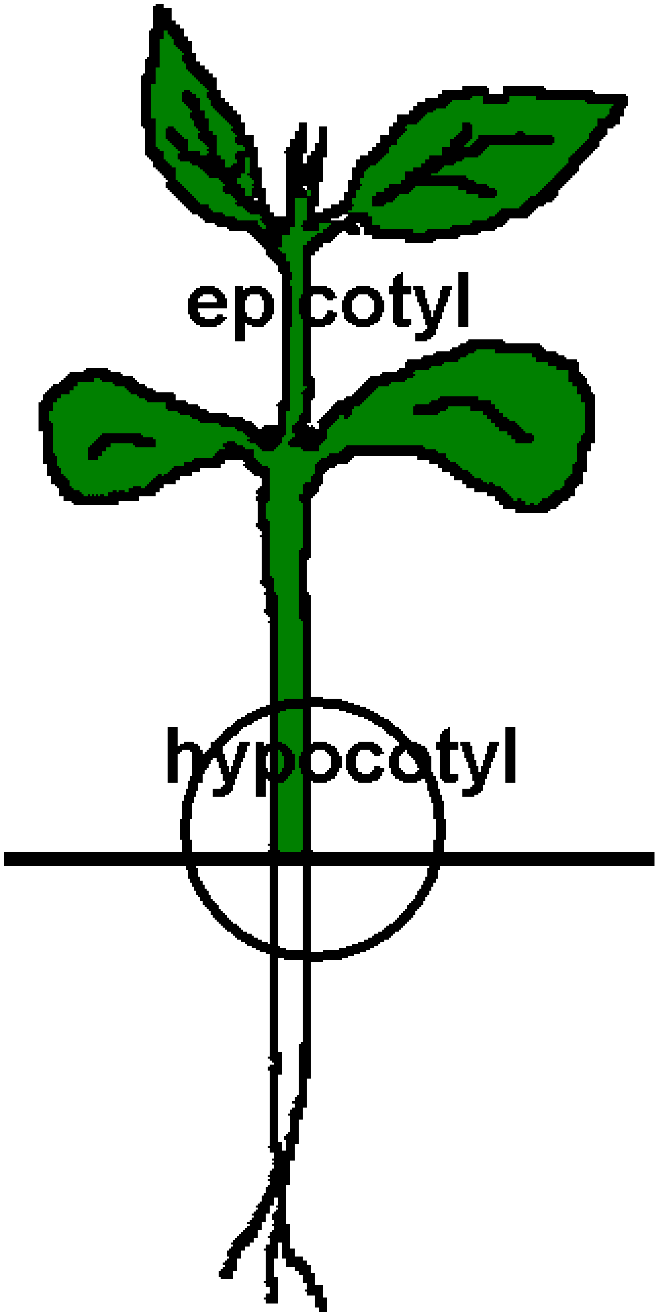
Types of plant body

- **Thallus** (flat, with non-differentiated organs)
- **Shoot** body (roots are absent)
- **Bipolar** body (root and shoot systems)

Organs of bipolar plant

- **Leaf**: flat lateral organ with restricted growth
- **Stem**: axial aerial organ with continuous growth
- **Root**: soil organ modified for absorption
- **Floral unit** (FU): stable element of generative system

Non-organs



- *Hypocotyl*: transition between stem and root
- *Epicotyl*: first internode of plant
- *Bud*: shoot "embryo"
- *Fruit*: temporary structure, ripe FU
- *Seed*: chimeric structure, has two or three genotypes

Organ systems: final

- Shoot system: vegetative and generative
- Root system

Origin of tissues and organs of plants

- Land colonization. Challenge: drying. Response: **epidermis** and **parenchyma**. Thallus body plan.
- New level of competition. Response: shoot body plan. Problem: big weight. Solution: **collenchyma**.
- Competition grows again. Respose: grow higher. Weight grows. Response: use dead cells in **sclerenchyma**.
- Competition grows again. Response: grow faster. Solution: **meristems**.
- Size of plant is too big for plasmodesmata transportations. Solution: vascular tissues, **xylem** and **phloem**. Here plants with sporophyte dominance win the competition.
- Size of plant is too big for osmotic absorption of water. Solution: **absorption tissues**, roots, bipolar body plan. Now they are independent from water as much as possible—with an exception of generative system...
- Shoot system make leaves, stems and **branches**. Plants are facing new challenge!

Summary

- Water deficit results in either sclerophyte or succulent adaptations
- Water excess results in hygrophyte or even hydrophyte adaptations

43 Shoot

43.1 Stem

Stem: definition and functions

- Axial vegetative organ of shoot with functions of support and transportation
- Other functions:
  A. Photosynthesis
  B. Storage
- Features:
  A. Radial structure
  B. No root hairs
  C. Continuous growth

43.2 Development of stem tissues

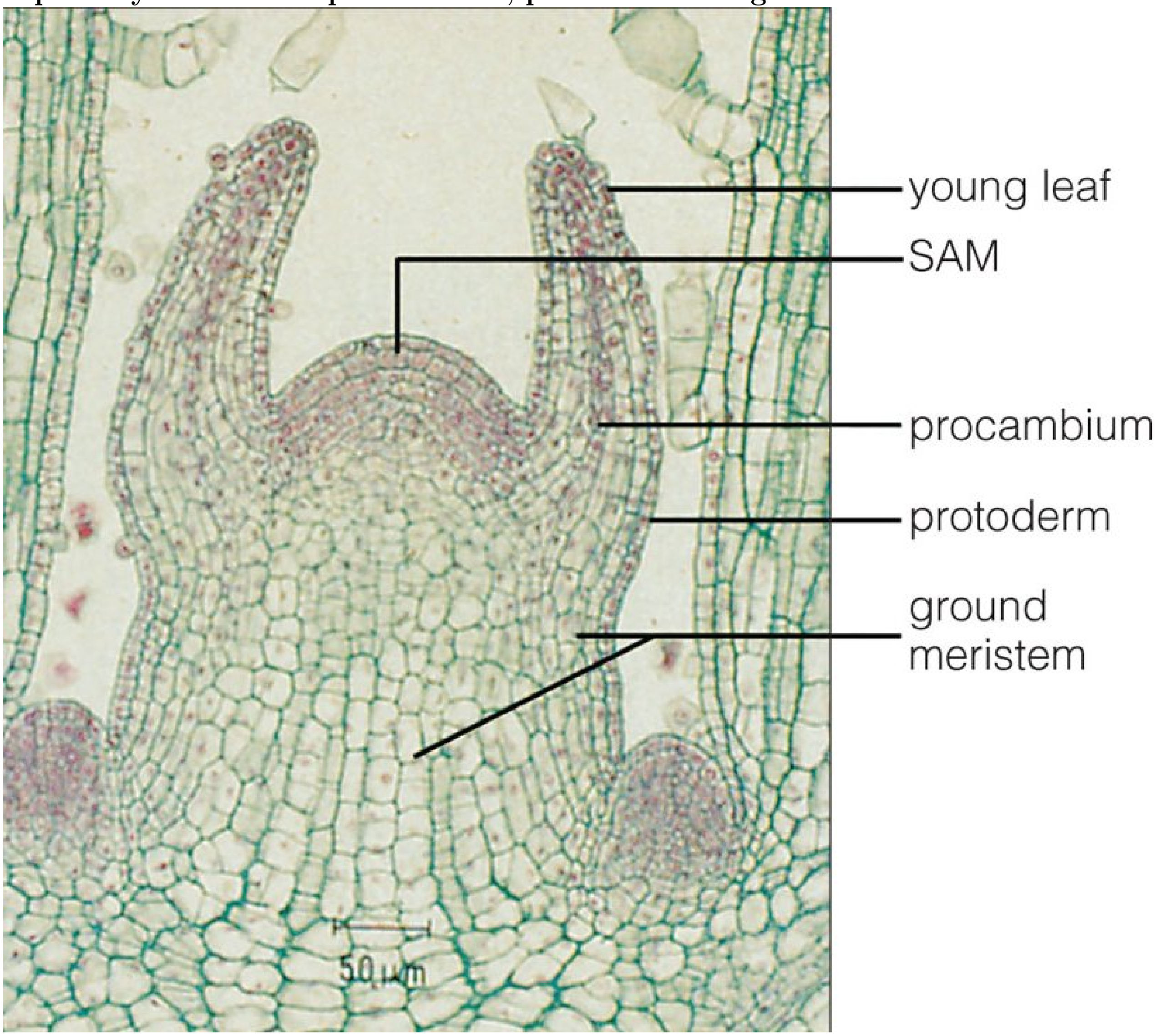
Protoderm to epidermis

- Stem apex meristem (SAM) produces **protoderm**
- Protoderm cells differentiate into epidermal cells

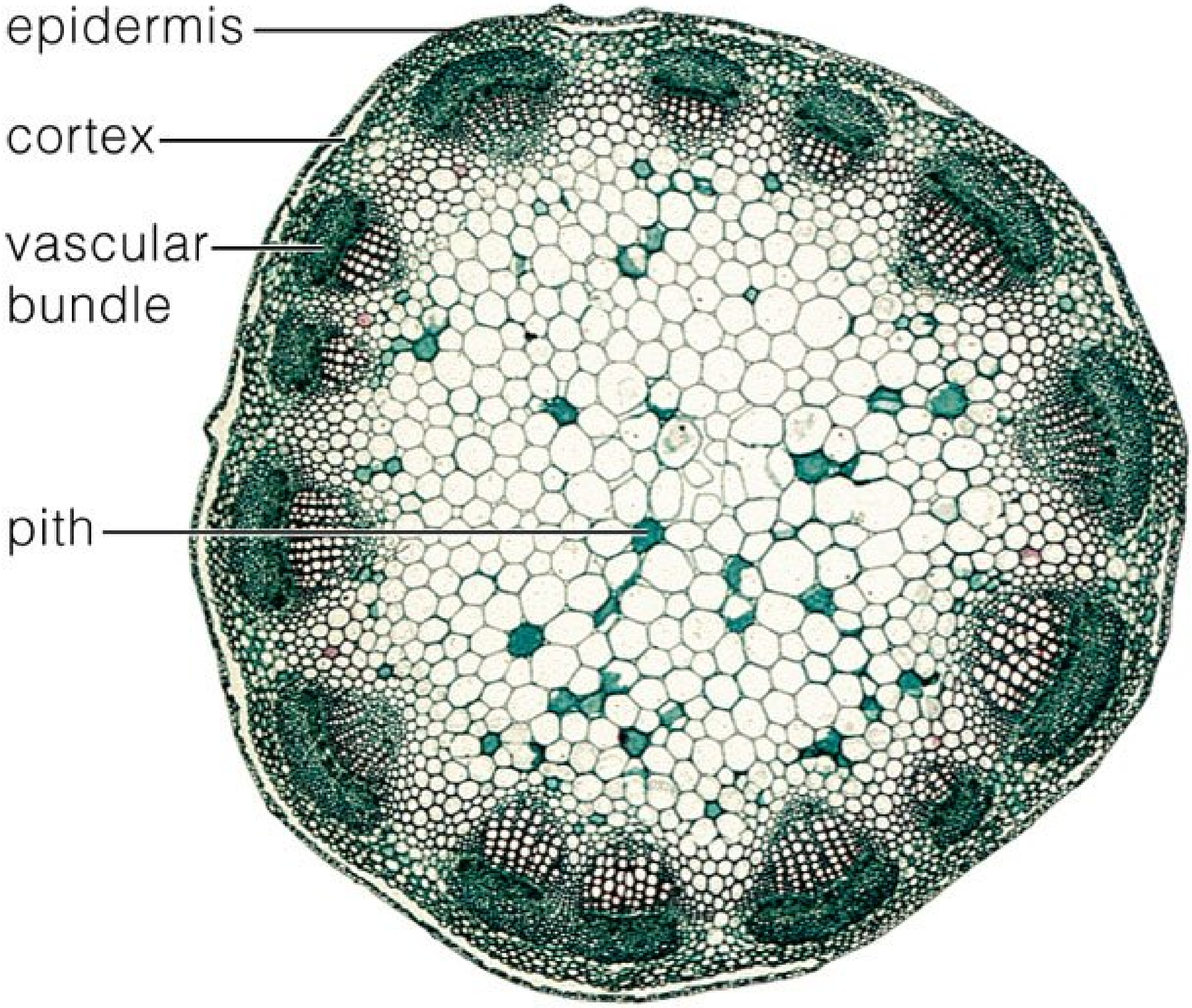
Ground meristem to cortex and pith

- SAM produces also **ground meristem**
- Ground meristem differentiates into **cortex** and **pith**
- Procambium raises between cortex and pith, it forms vascular bundles or vascular cylinder

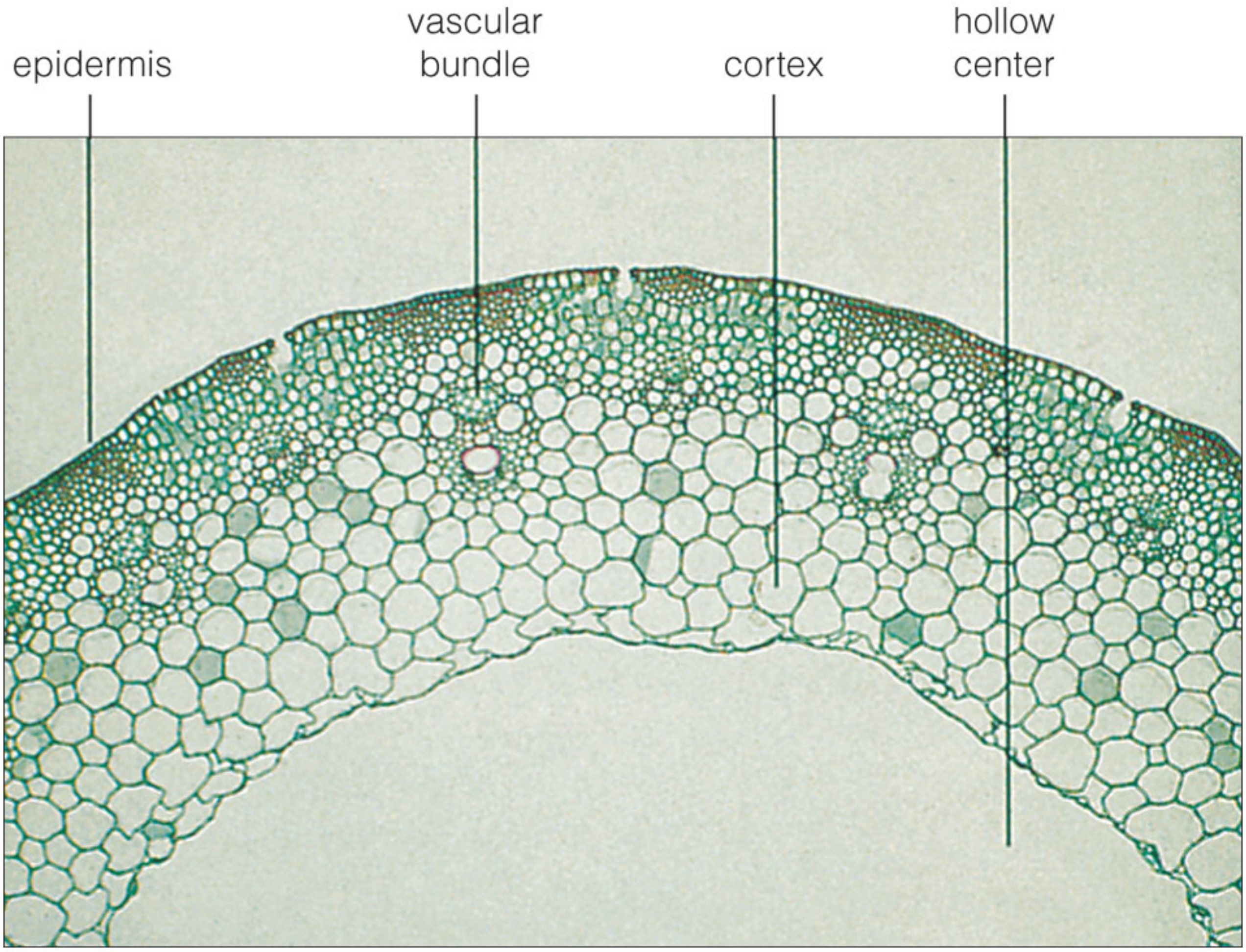
Three primary meristems: procambium, protoderm and ground meristem



Young stem with primary tissues



Older stem with hollow in the center

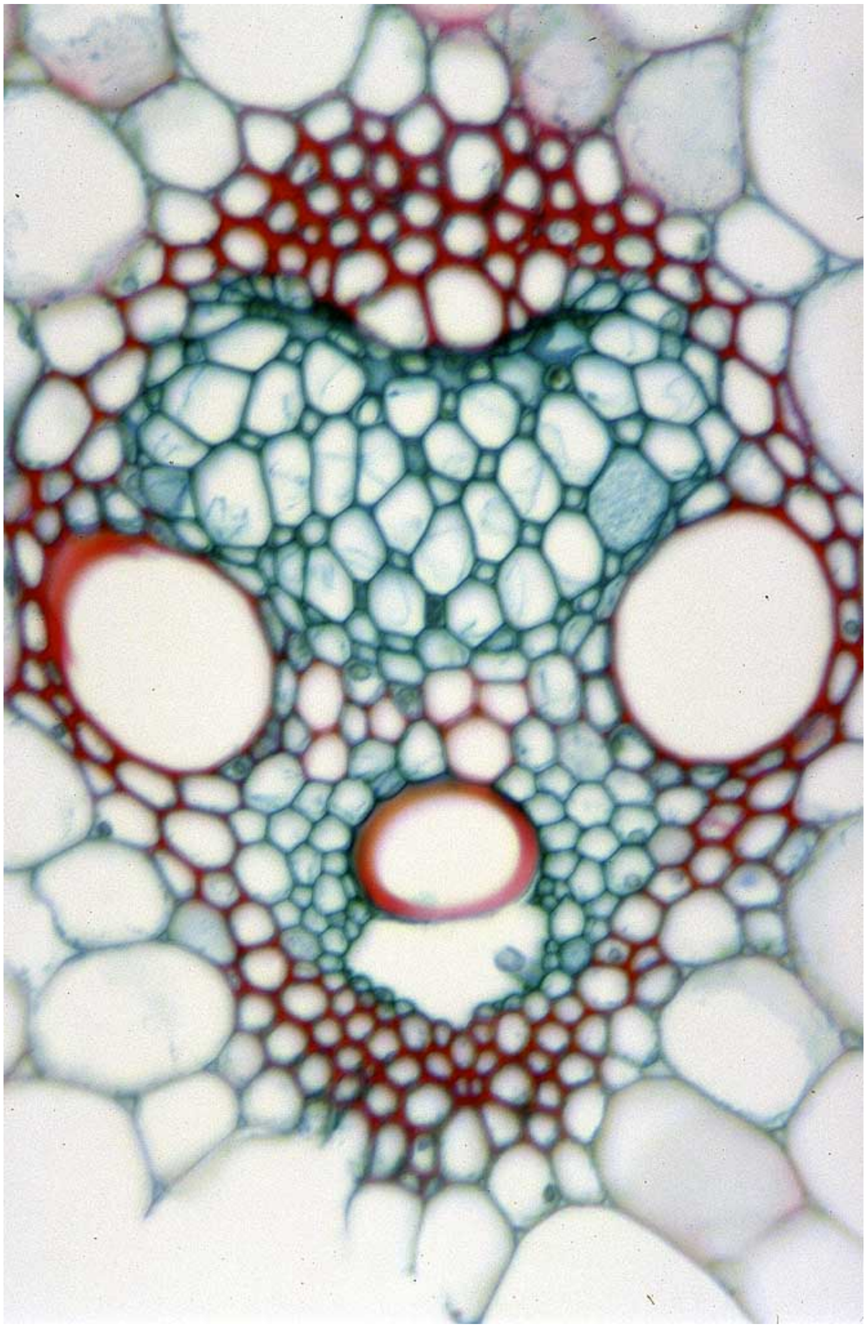


Procambium to xylem and phloem

- Outer layers of procambium form **primary phloem**
- Inner layers become **primary xylem**
- Middle layer could be completely spent **or** will make cambium for the secondary thickening
- Sometimes outermost layers of procambium form **pericycle** (parenchyma cells)
- In some cases, inner layers of cortex could form **endoderm**

43.3 Anatomy of the primary stem

Vascular bundle (monocot)



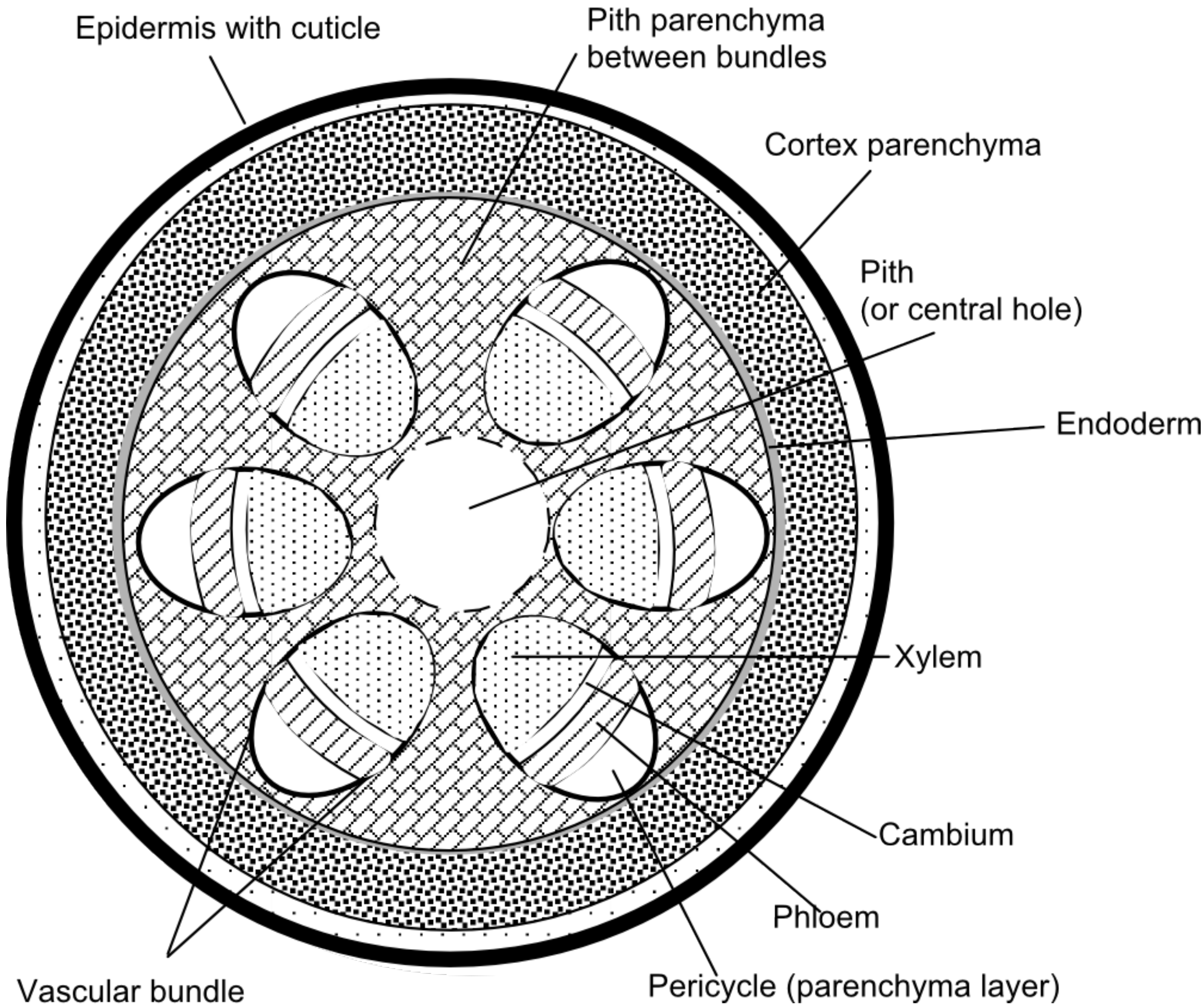
Corn (*Zea mays*) mature stem cross-section showing single vascular bundle, Brightfield (LM ×400)

Summary

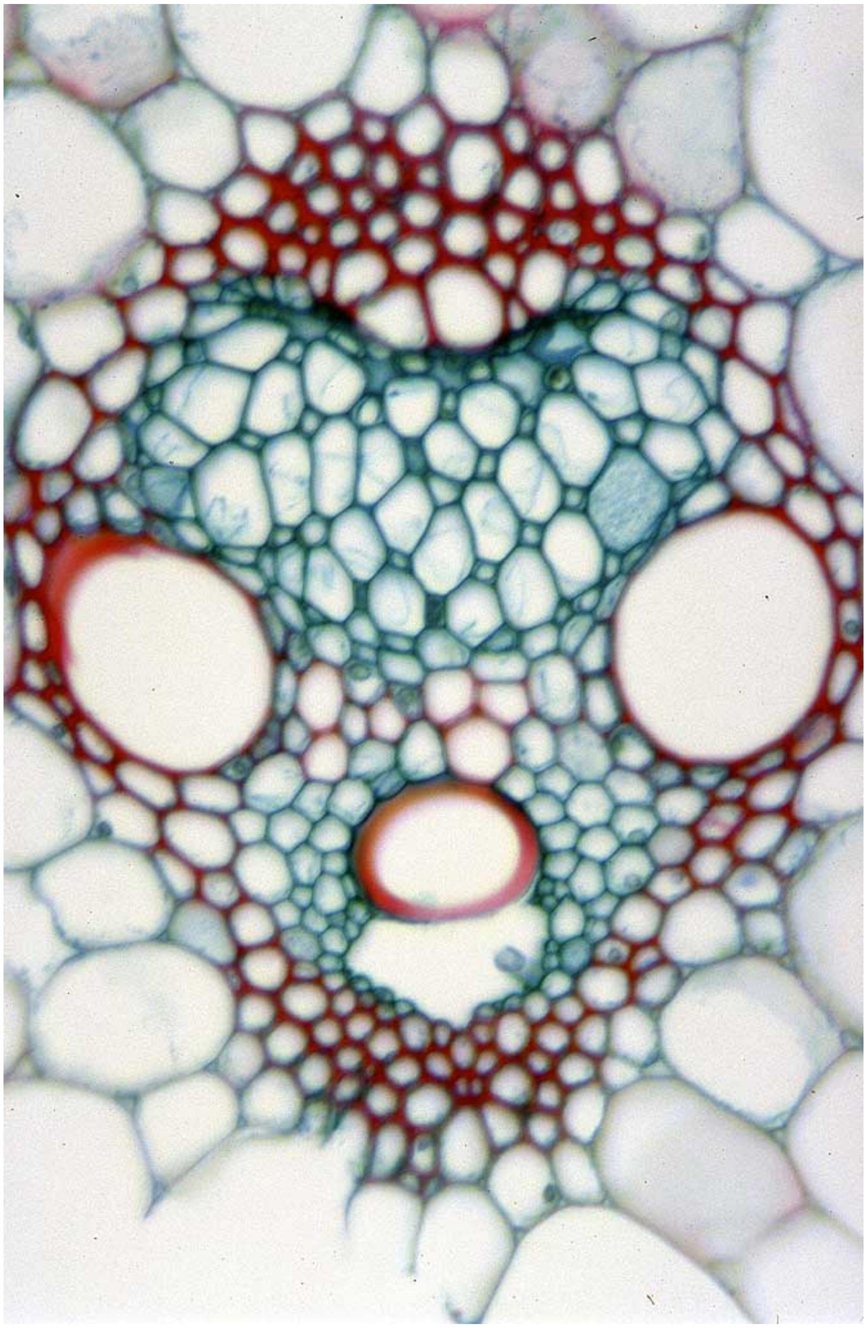
- SAM produces **protoderm** and **ground meristem**, ground meristem differentiates into **cortex** and **pith**
- Procambium forms **vascular bundles** or vascular cylinder

43.4 Anatomy of the primary stem

Primary structure of stem

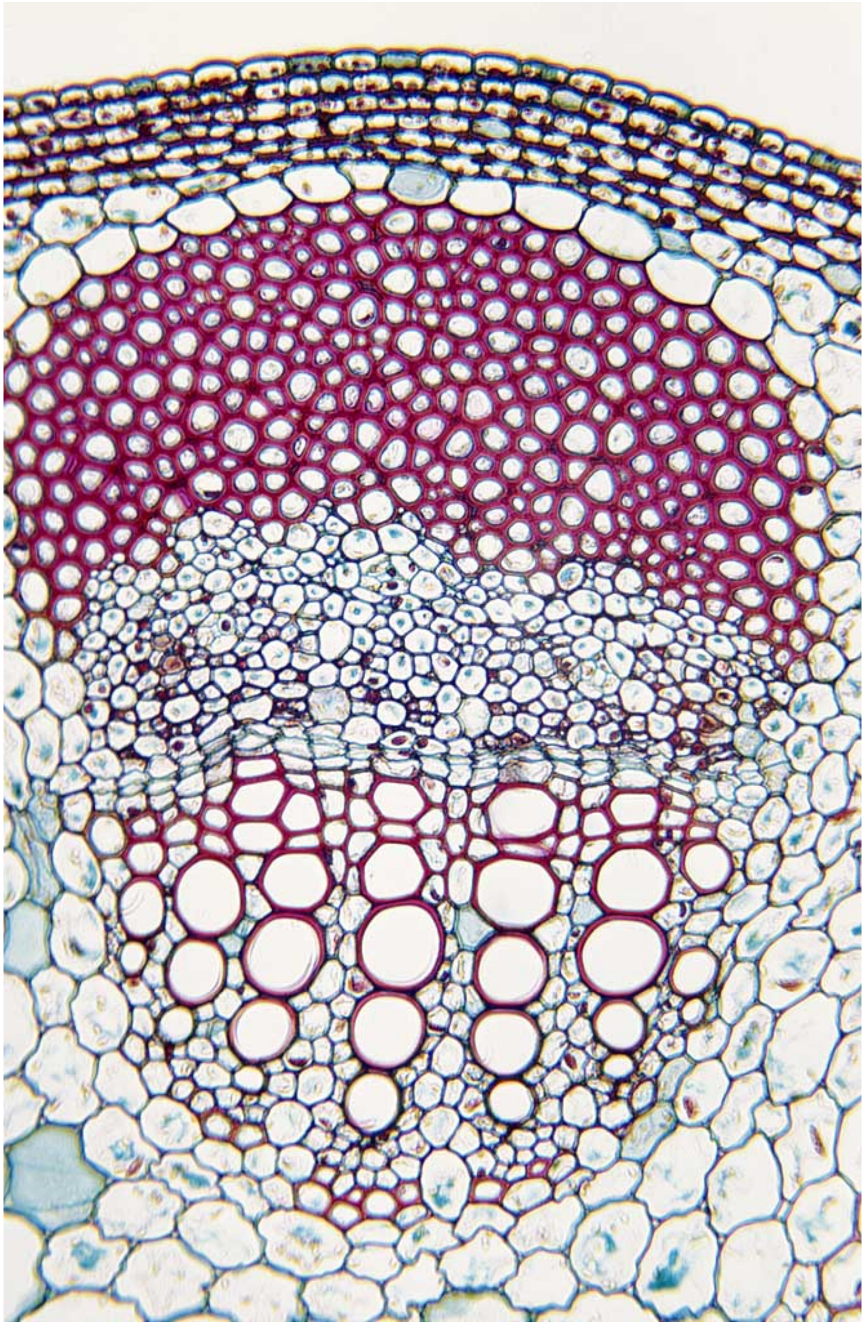


Vascular bundle (monocot)

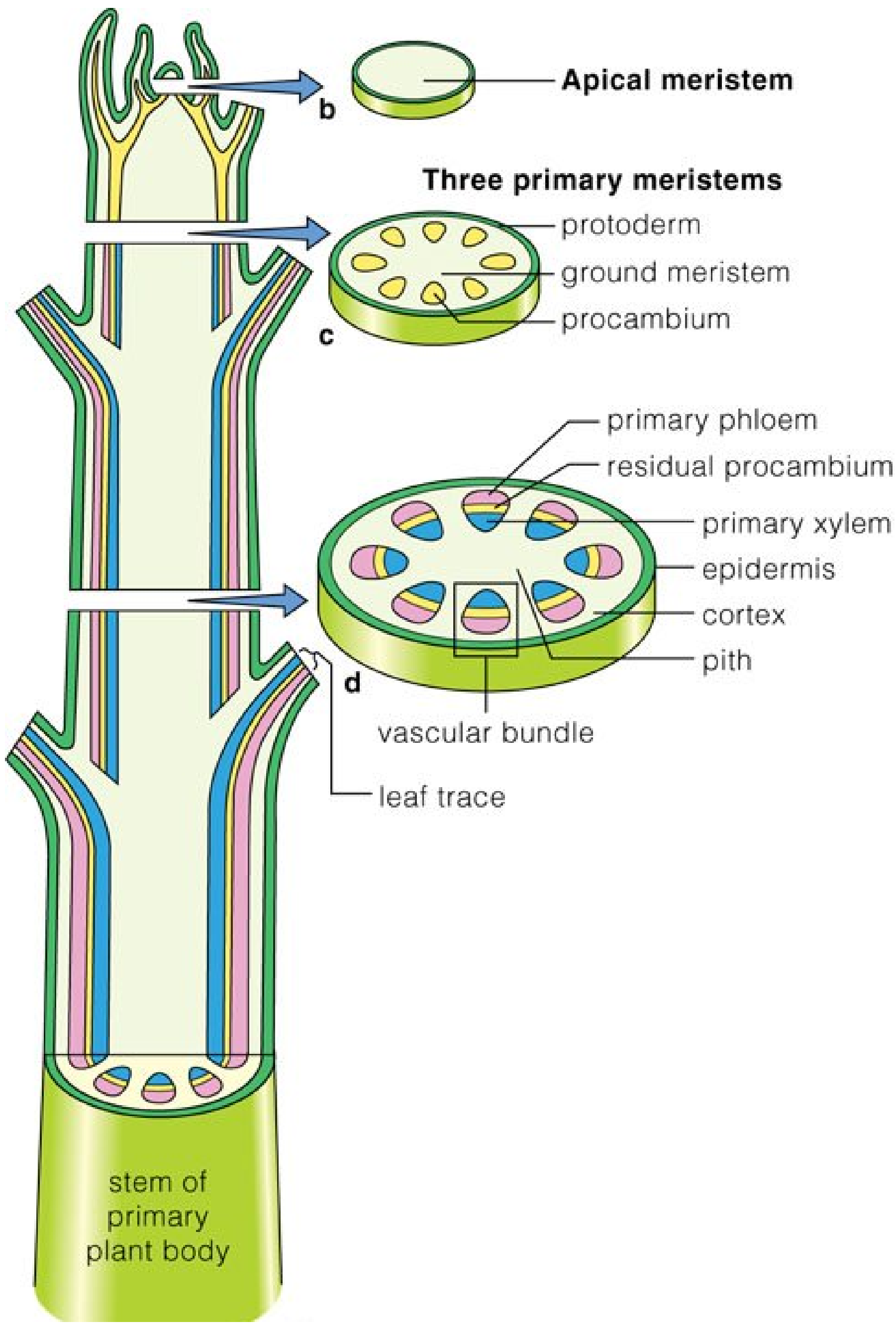


Corn (*Zea mays*) mature stem cross-section showing single vascular bundle, Brightfield (LM $\times 400$)

Vascular bundle (asterid)


Wild Sunflower (*Helianthus* sp.) with nearly mature vascular bundle (LM ×35)

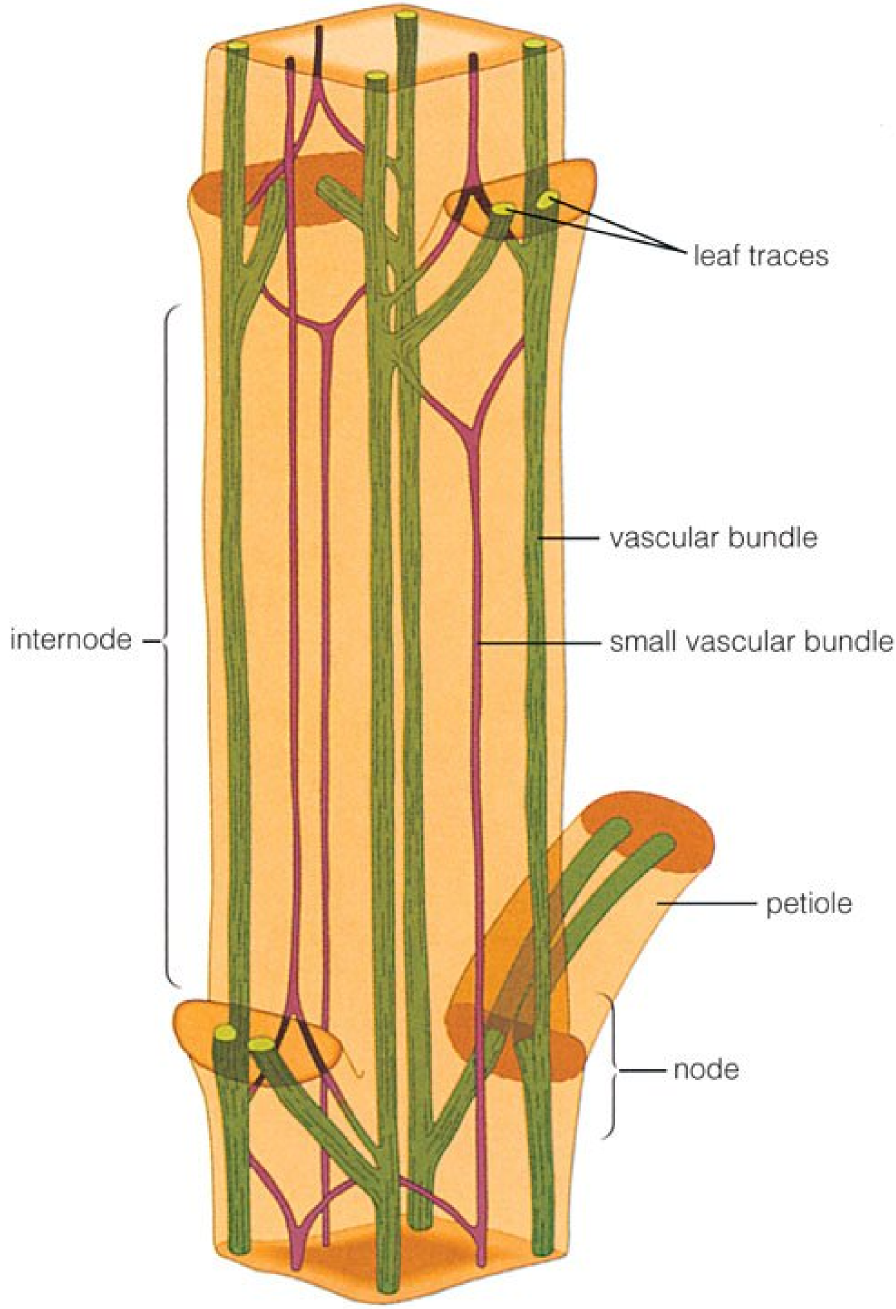
Origin of vascular bundles



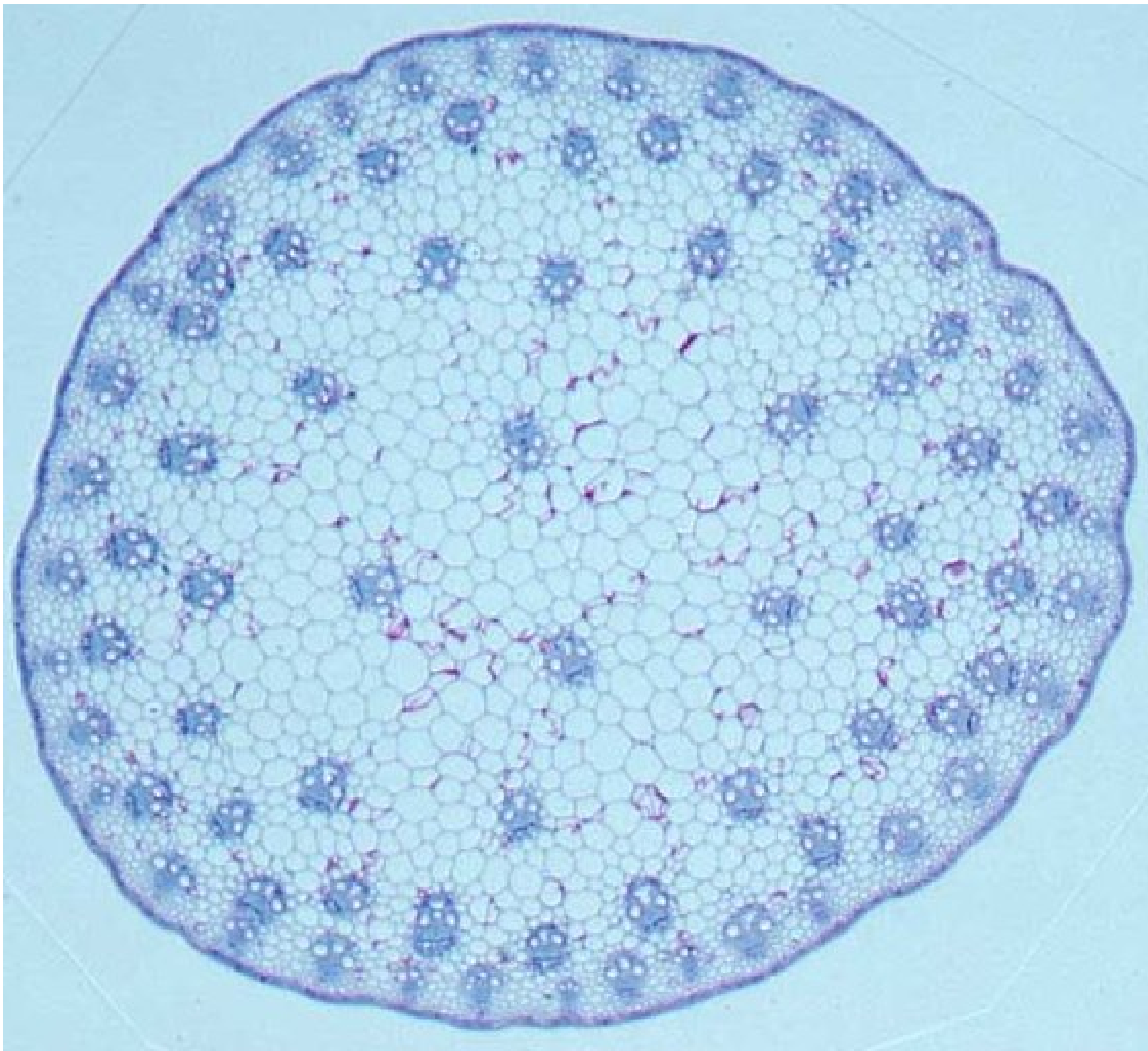
Vascular bundles

- Vascular bundles connect leaves and stems
- In many plants, they form **ring** on the cross-section of stem ("dicot" stem)
- Monocot stems usually have **dispersed** vascular bundles

Vascular bundles and leaf traces



Monocot stem

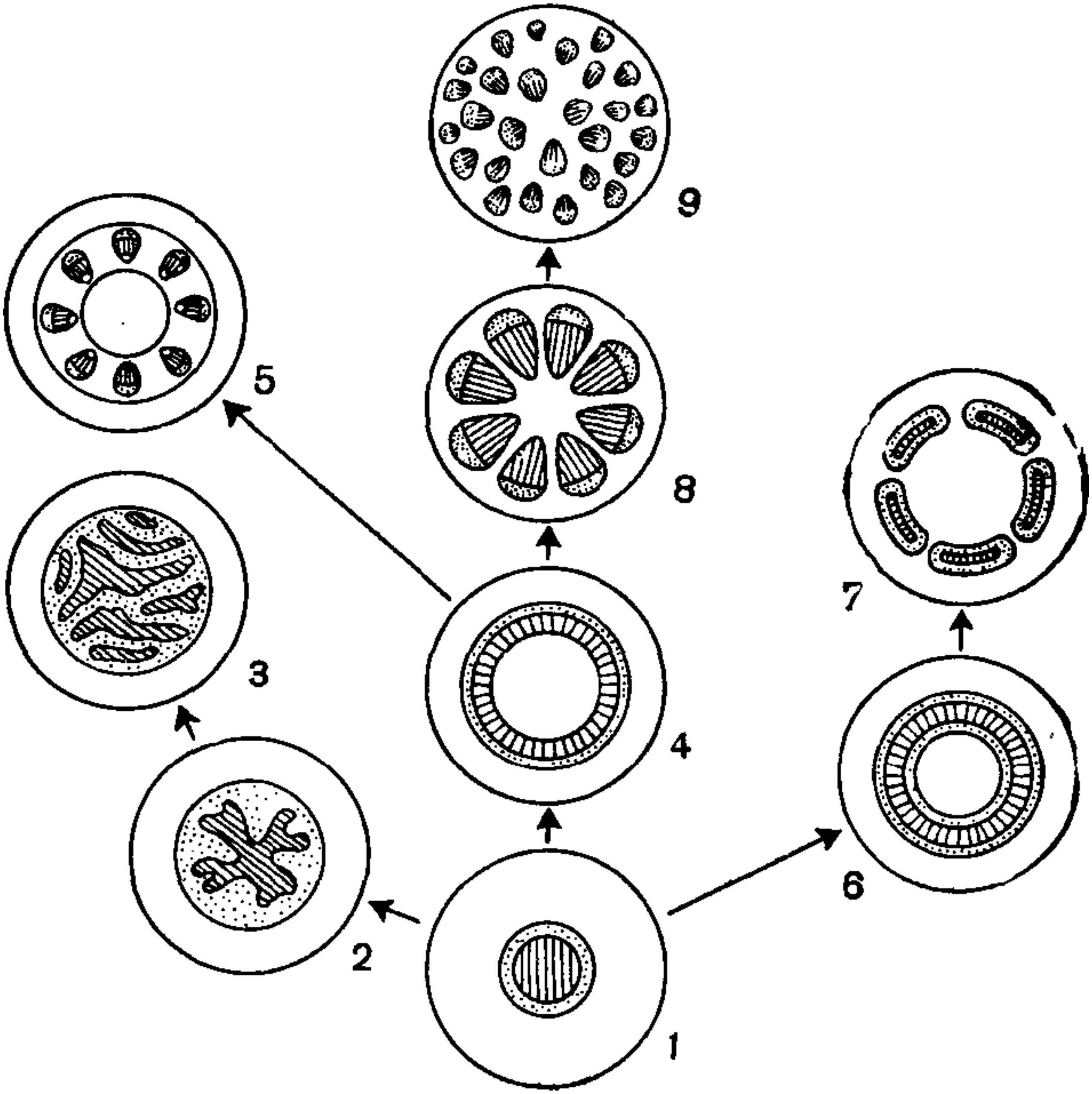


Corn (*Zea mays*) stem (LM $\times 4$)

Steles

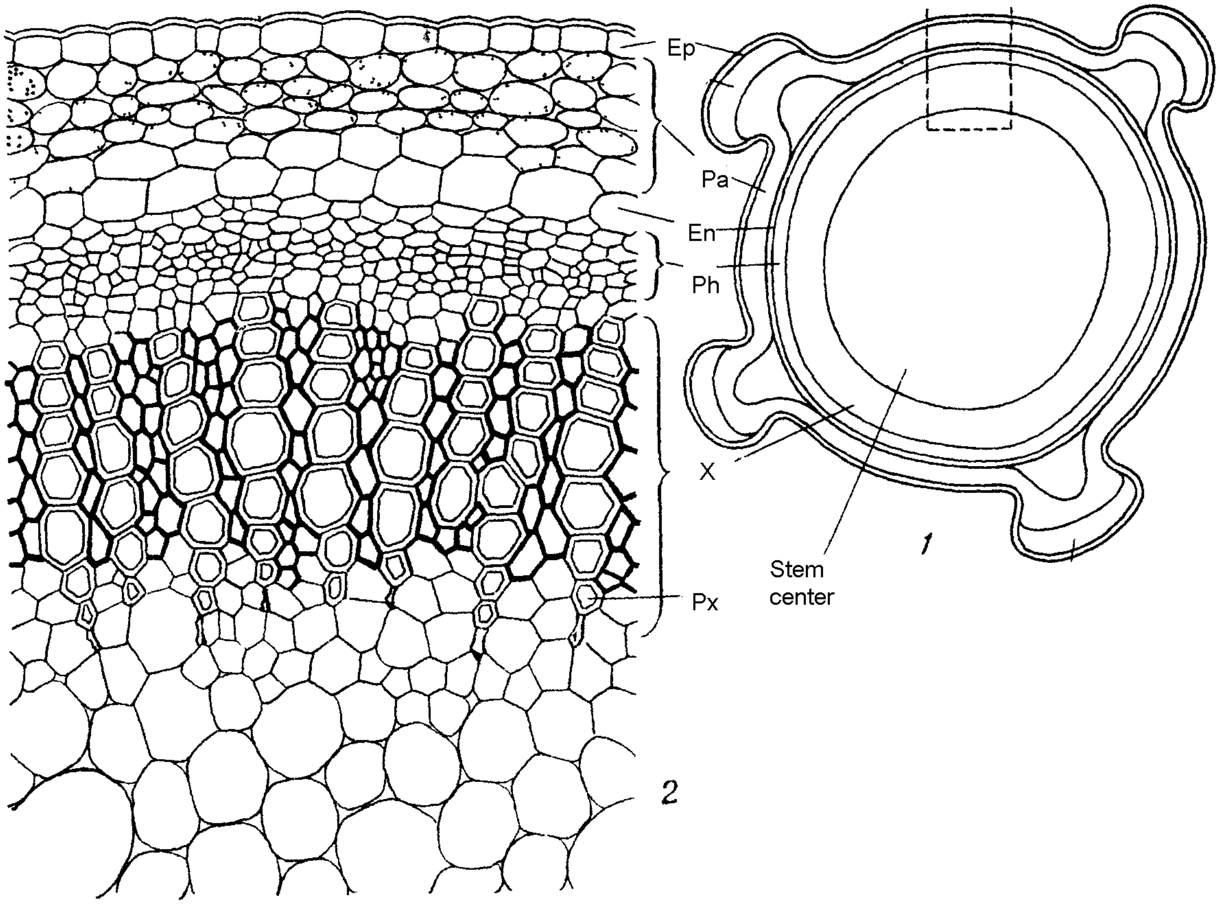
- **Stele** is an overall configuration of primary vascular system of plant stem
- The most important kinds of steles are: **protostele**, **solenostele**, **eustele** and **ataktostele**

Diversity of steles



(1) is protostele, (4) solenostele, (8) eustele ("dicot" stem), (9) ataktostele (monocot stem)

Vascular cylinder: alternative to ring of bundles



Sometimes, vascular bundles are so dense that they form almost a cylinder. We may call this vascular cylinder "solenostele" (#4 on the scheme of steles)

43.5 Components of shoot

Components of vegetative shoot system

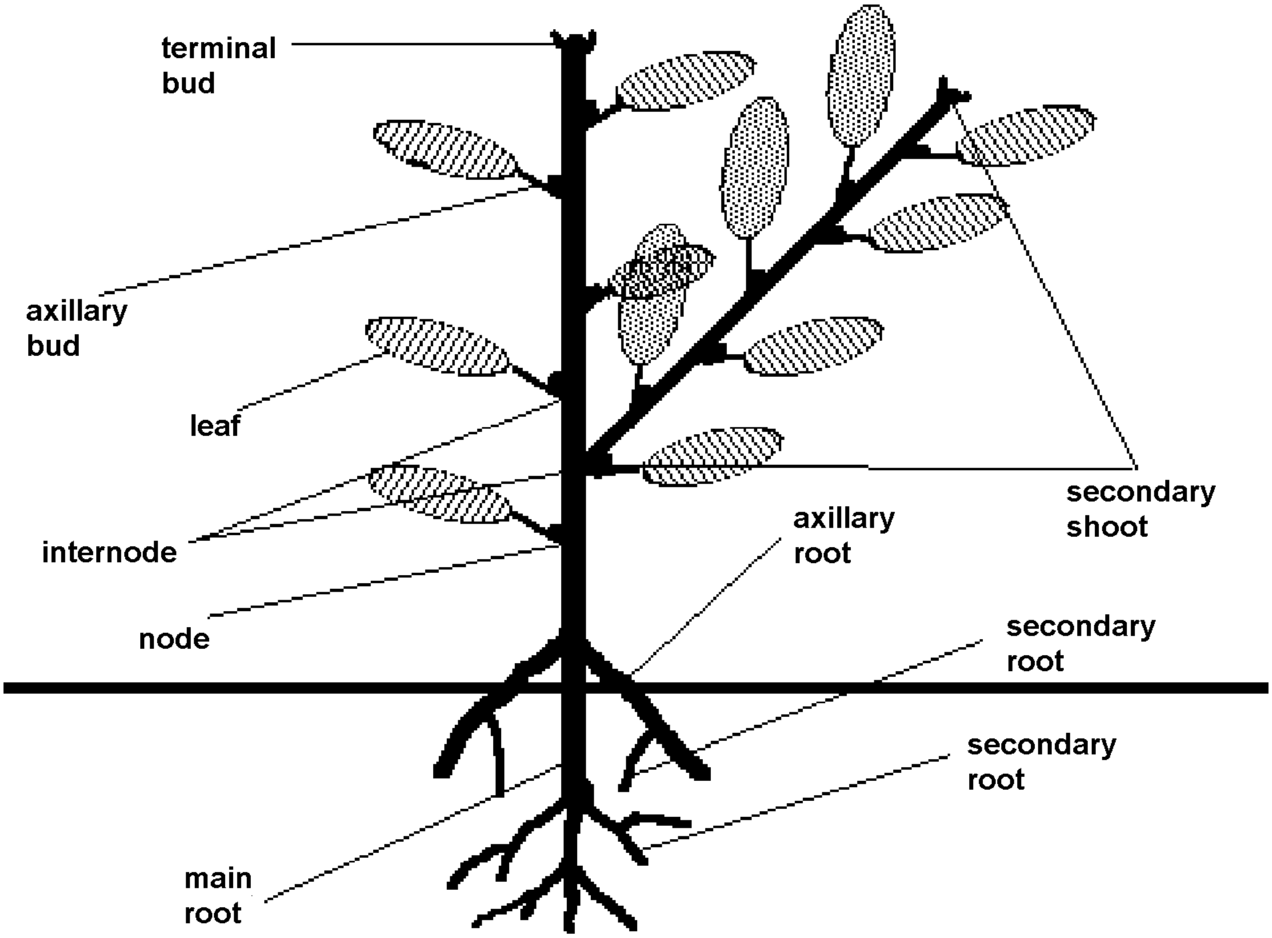
A. Main and secondary shoots

B. Terminal and axillary (lateral) buds

C. Nodes and internodes

D. Leaves

Components of shoot

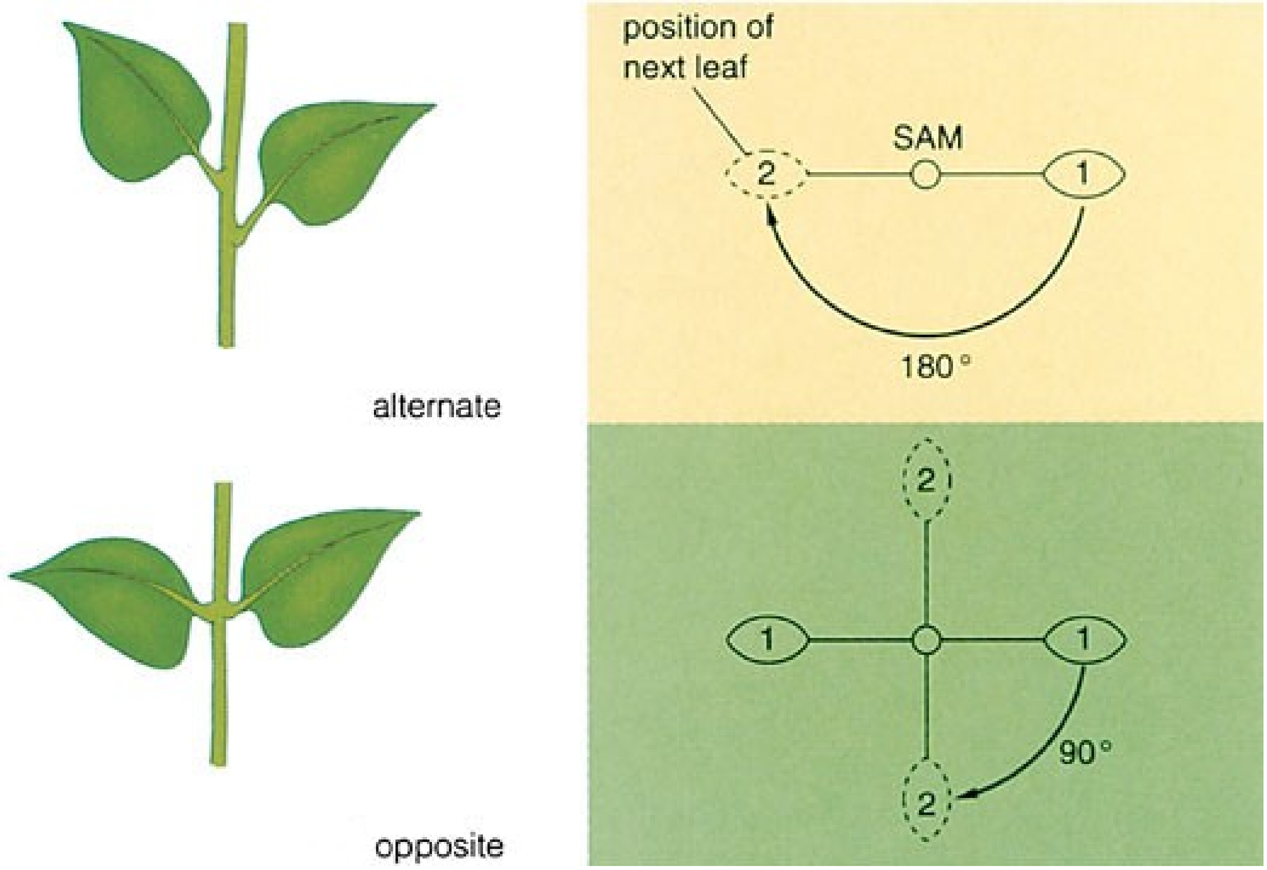


43.6 Phyllotaxis

Arrangement of leaves: phyllotaxis

- One leaf per node: **spiral**, or **alternate** arrangement
- Two leaves per node: **opposite** arrangement, they may be:
  - All in same plane
  - Each pair will rotate on 90°
- > 2 leaves per node: **whorled** arrangement (each whorl can also rotates)
- Each type of phyllotaxis has its own *angle of divergence*

Alternate and opposite phyllotaxes



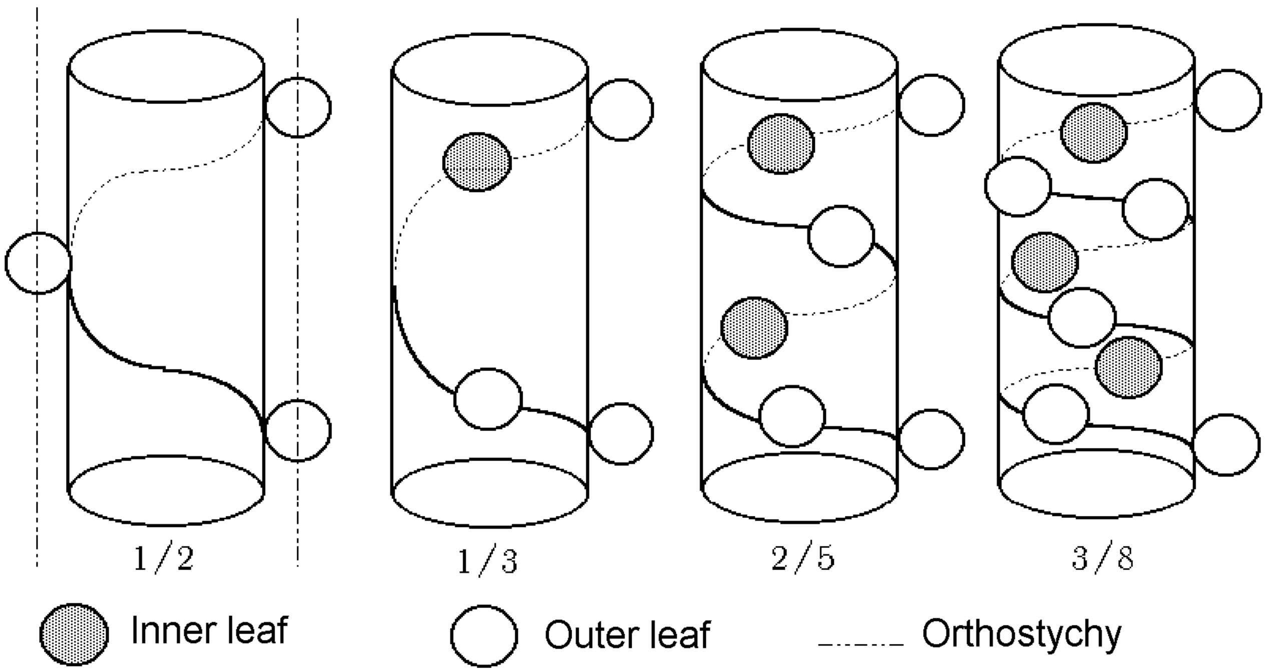
Spiral phyllotaxis: Fibonacci rule

- Multiple types of leaf spiral leaf arrangement mostly follow **Fibonacci rule**
- Formulas of leaf arrangements is very similar to Finobacci fractions: $\frac{1}{2}$, $\frac{1}{3}$, $\frac{2}{5}$, $\frac{3}{8}$, $\frac{5}{13}$, *et cetera*
- Numerator is number of spiral circulations, denominator is number of leaves in a series (counted from zero)
- Denominator gives the number of **orthostychy** (this is plural)

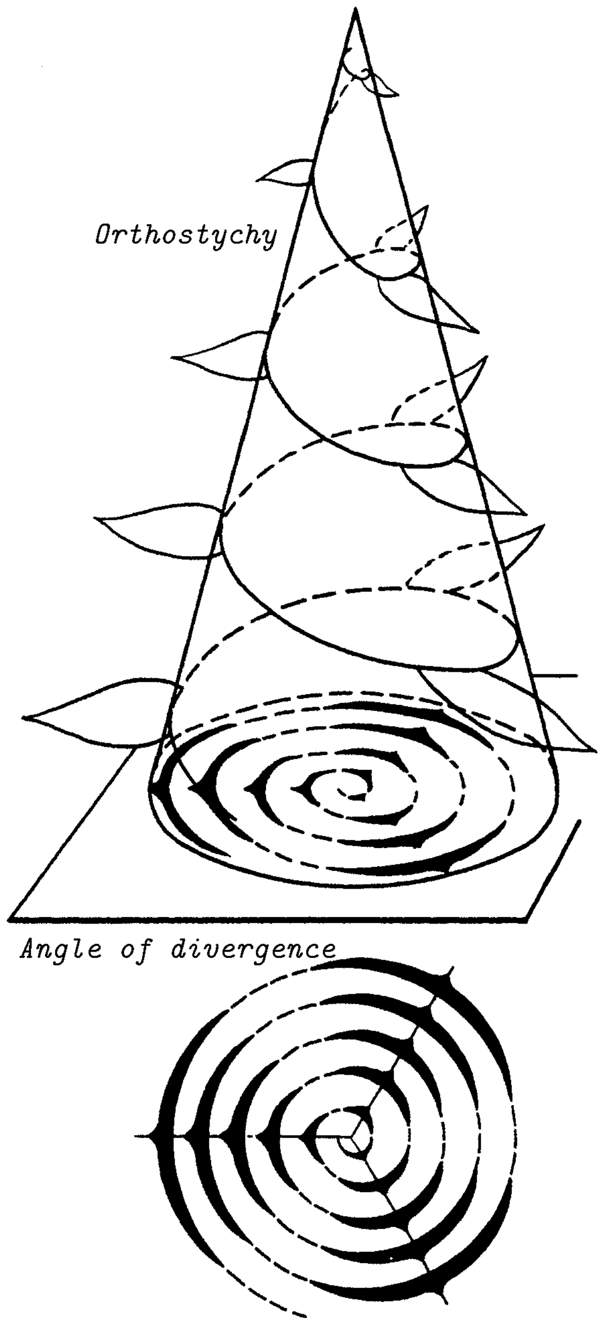
Spiral phyllotaxis: how to make a formula

- Take a branch, find any leaf (it will be leaf #0)
- Find the second one which is located in the same position (exactly above or exactly below leaf #0)
- Count how many leaves are in this series (start from 0), this will be a denominator
- Imagine (or use a real thread) a spiral which go from leaf #0 to the last leaf of series, count how many times this spiral circulate the stem—this is a numerator

Spiral phyllotaxis: orthostychy



Spiral phyllotaxis: angles of divergence for 1/3



Final question (2 points)

What is procambium?

For Further Reading

References

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

Outline

44 Questions and answers

44.1 Quiz

Quizes

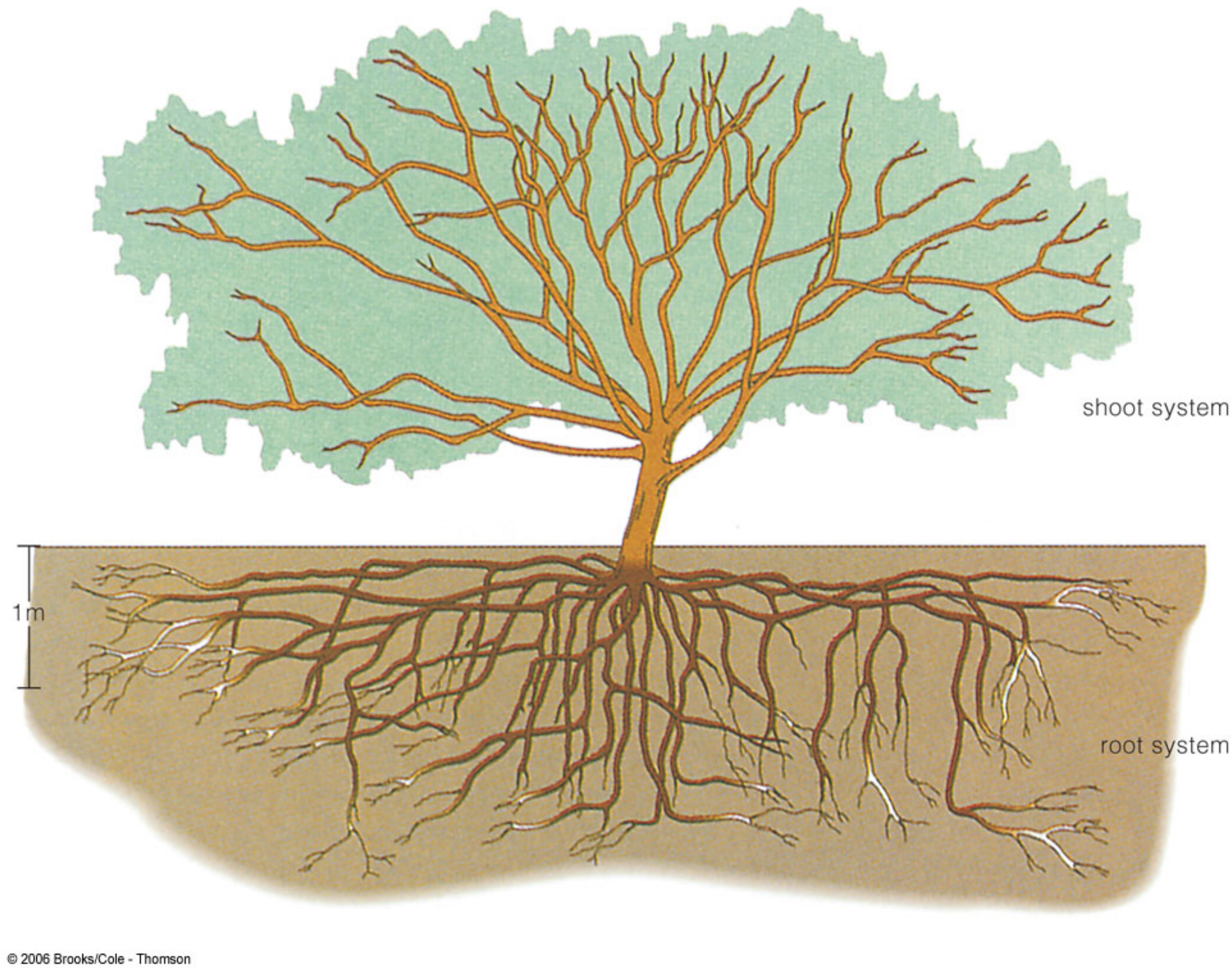
...

- ...

45 Root

45.1 Root morphology

Root system and shoot system



Definition and functions

- Axial vegetative organ with a function of soil nutrition
- Other functions:

  A. Anchor

B. Synthesis

C. Storage

D. Communication

- Features:

A. No leaves

B. Geotropic growth

C. Locates in soil or water

Types of roots

- Primary root: originates from root of seedling
- Secondary (lateral) roots: originate from primary roots
- Adventitious roots: originate from stems

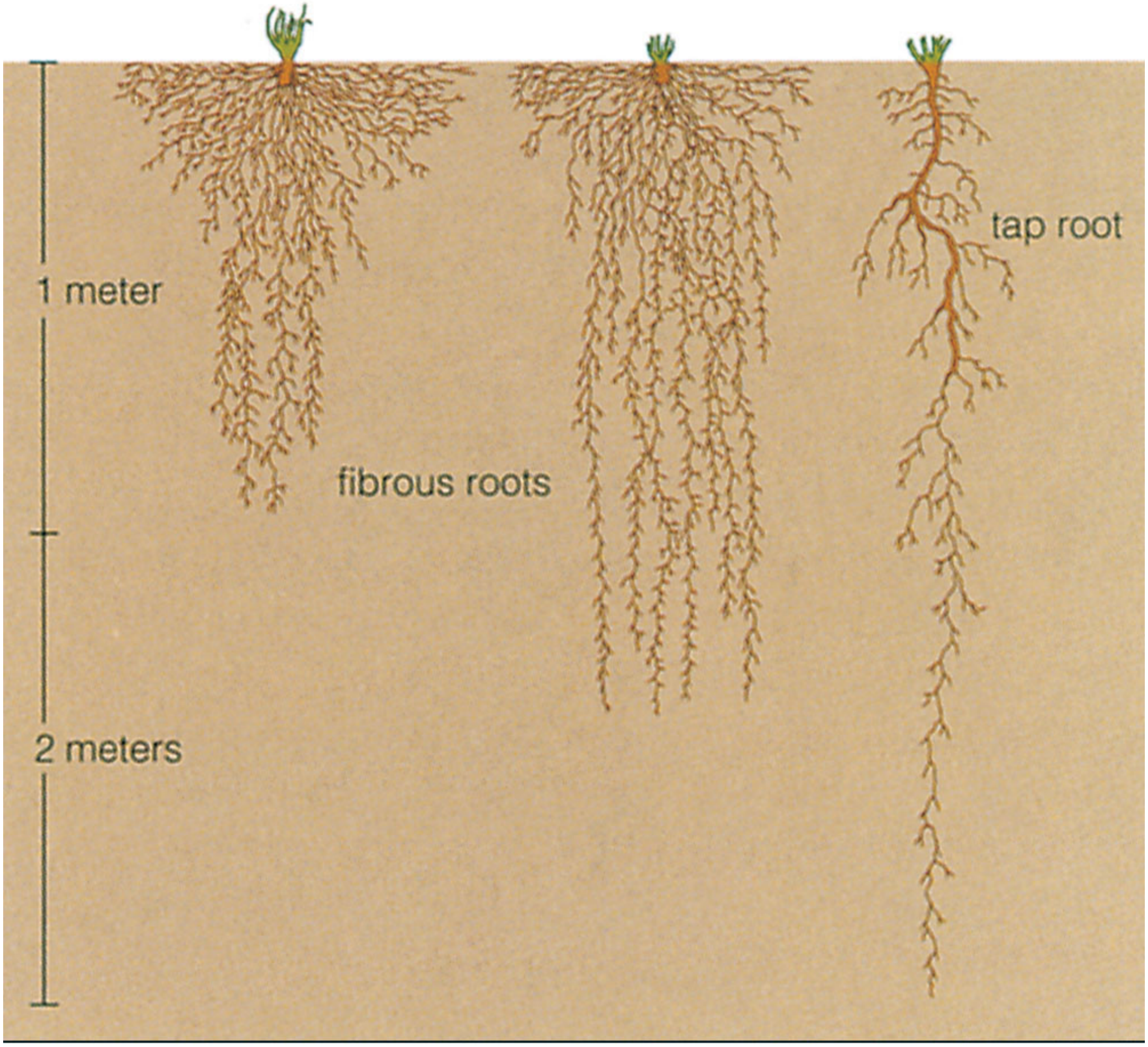
Primary root

Adventitious roots

Root systems

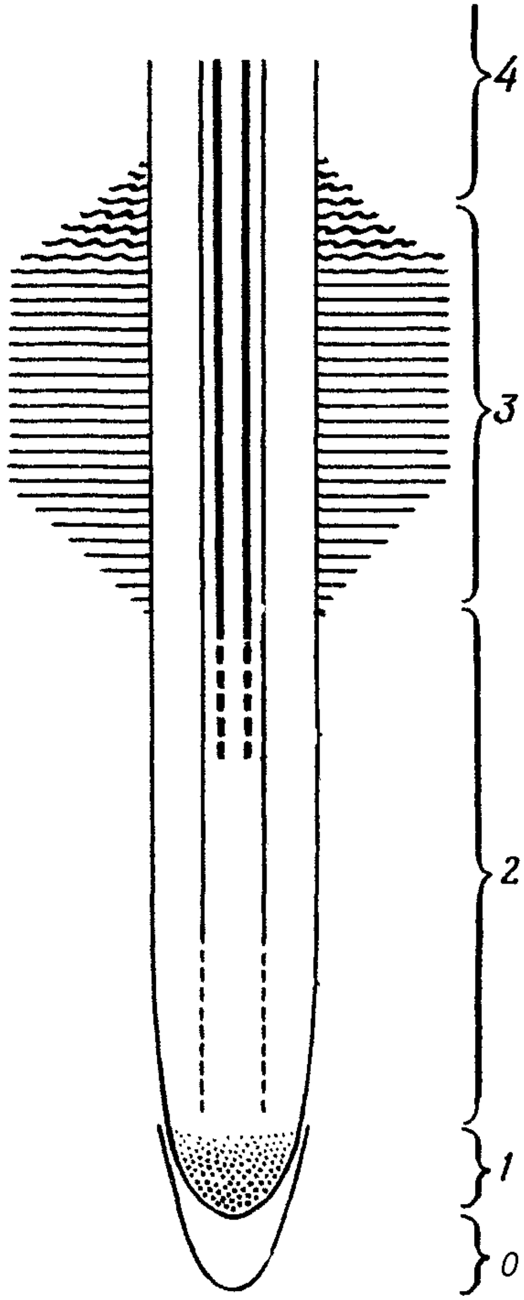
- Tap root system: with well developed primary root (most seed plants)
- Fibrous root system: without clearly visible primary root (monocots, ferns)

Fibrous and tap root systems



45.2 Anatomy and development of roots

Root zones



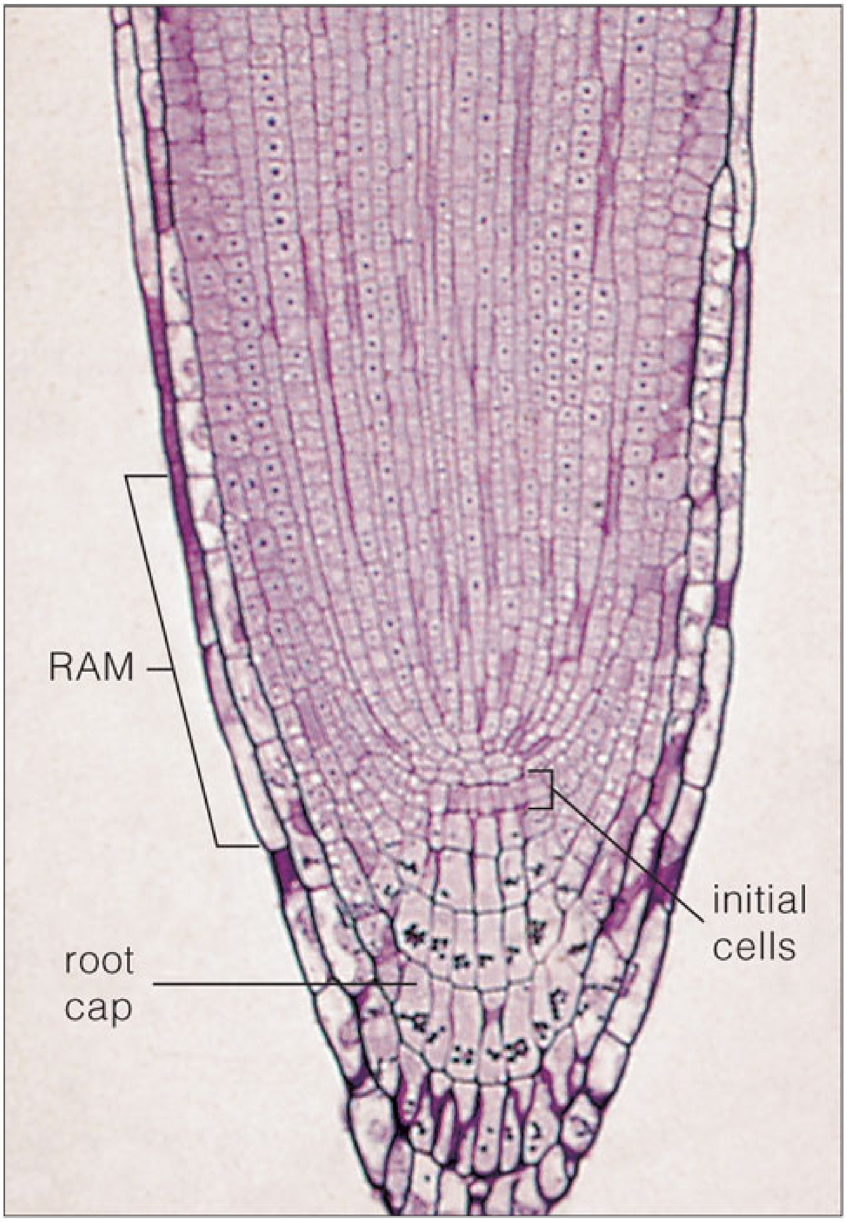
- Root cap
- Root meristem
- Elongation zone
- Absorption zone
- Maturation zone

Structure of root tip

- Initial cells (quiescent center)
- RAM

- Root tip growing both forward (root cap) and backward (other root tissues), initial cells determine the direction of growth
- If root tip touch barrier, it starts to make rotating movements

Root tip



Periphery of root

- Rhizodermis (rhizoderm, root epidermis): fast-degrading cells
- Cortex, which includes also:
  - Endodermis (endoderm): 1-cell layer with specialized cell walls, located on the border with vascular cylinder

  - And (sometimes) exodermis (exoderm): similar to endoderm but located just under rhizodermis

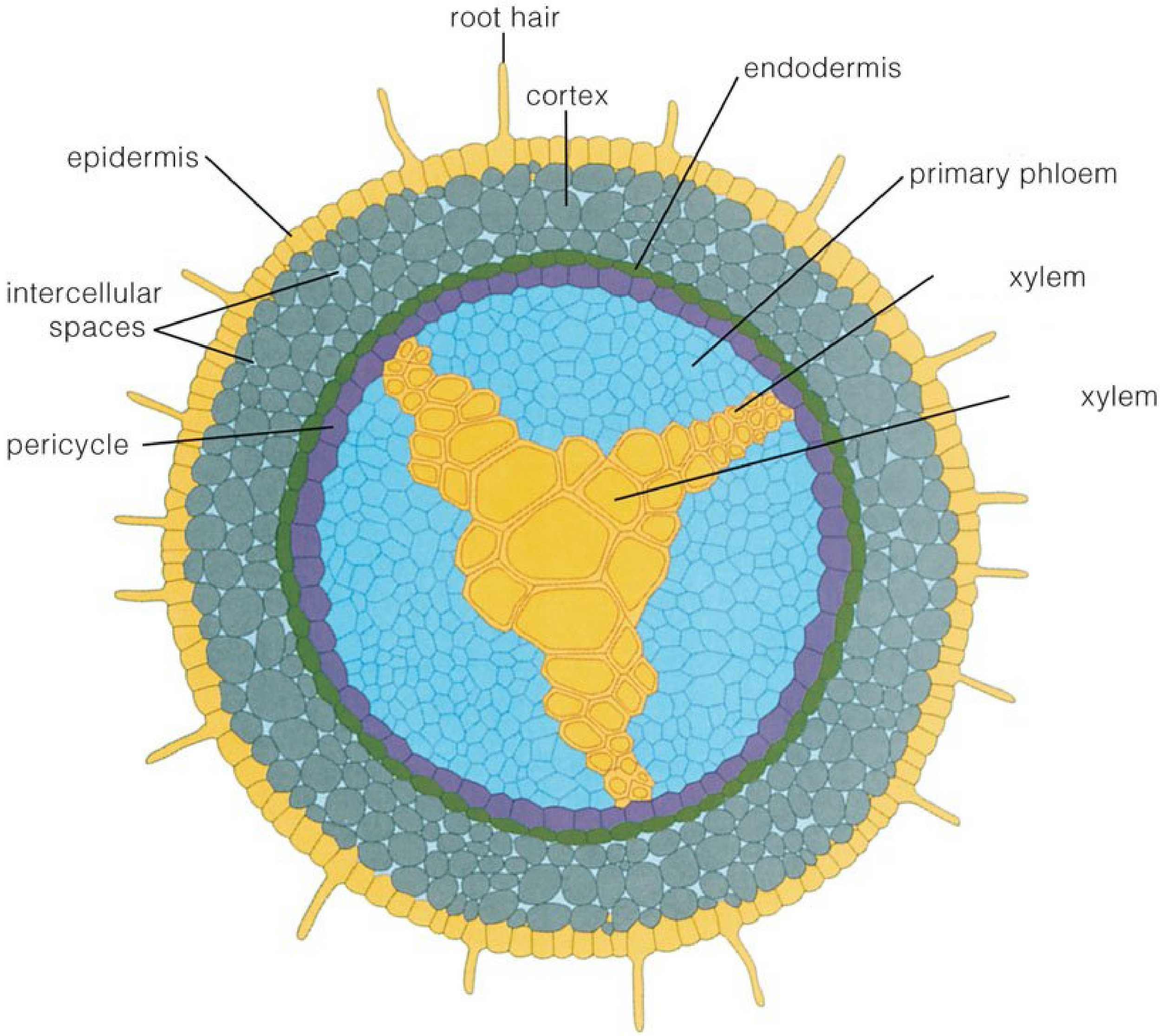
- In some plants (i.e., orchids), cortex modified into velamen

Root center: vascular cylinder

- Pericycle
- Vascular tissues located in the center
- No central hollow, central parenchyma presents in monocot roots

45.3 Anatomy and development of roots

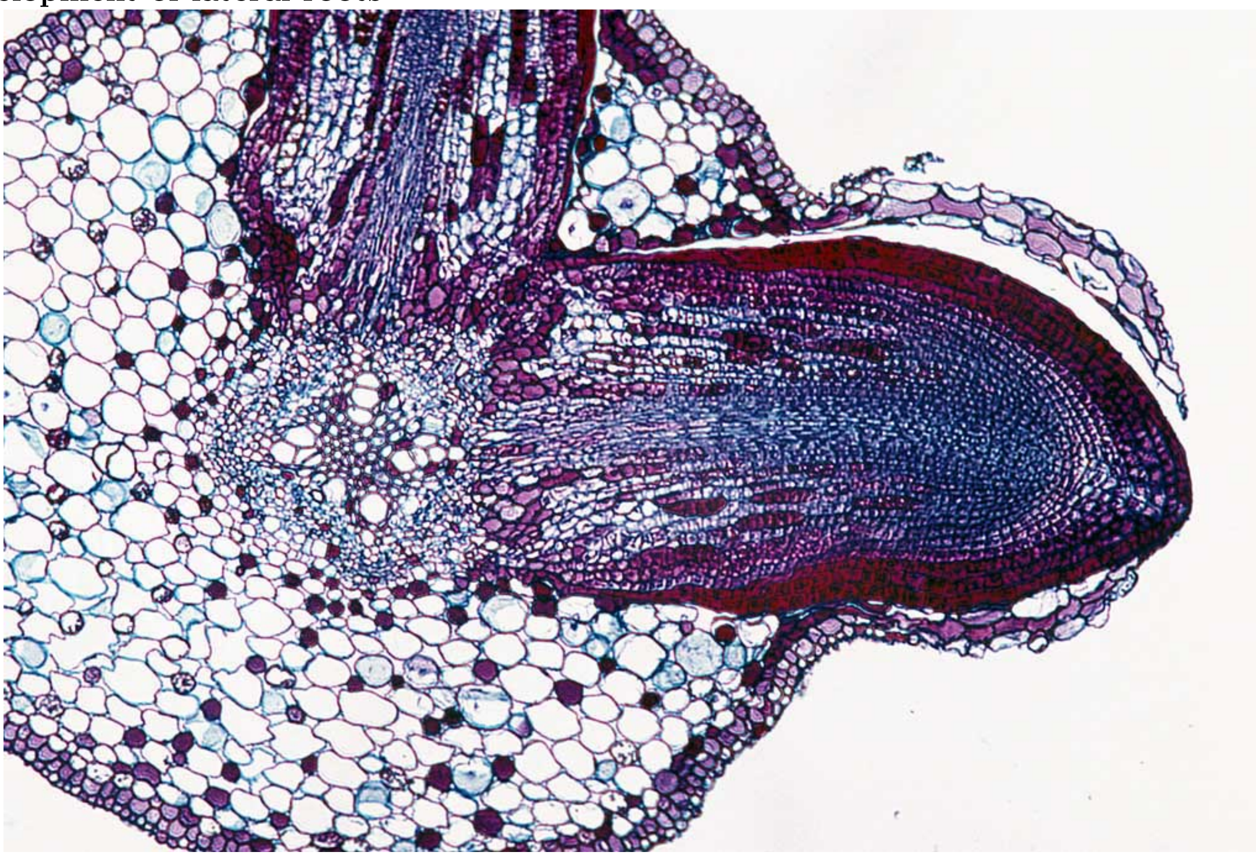
Anatomy of root



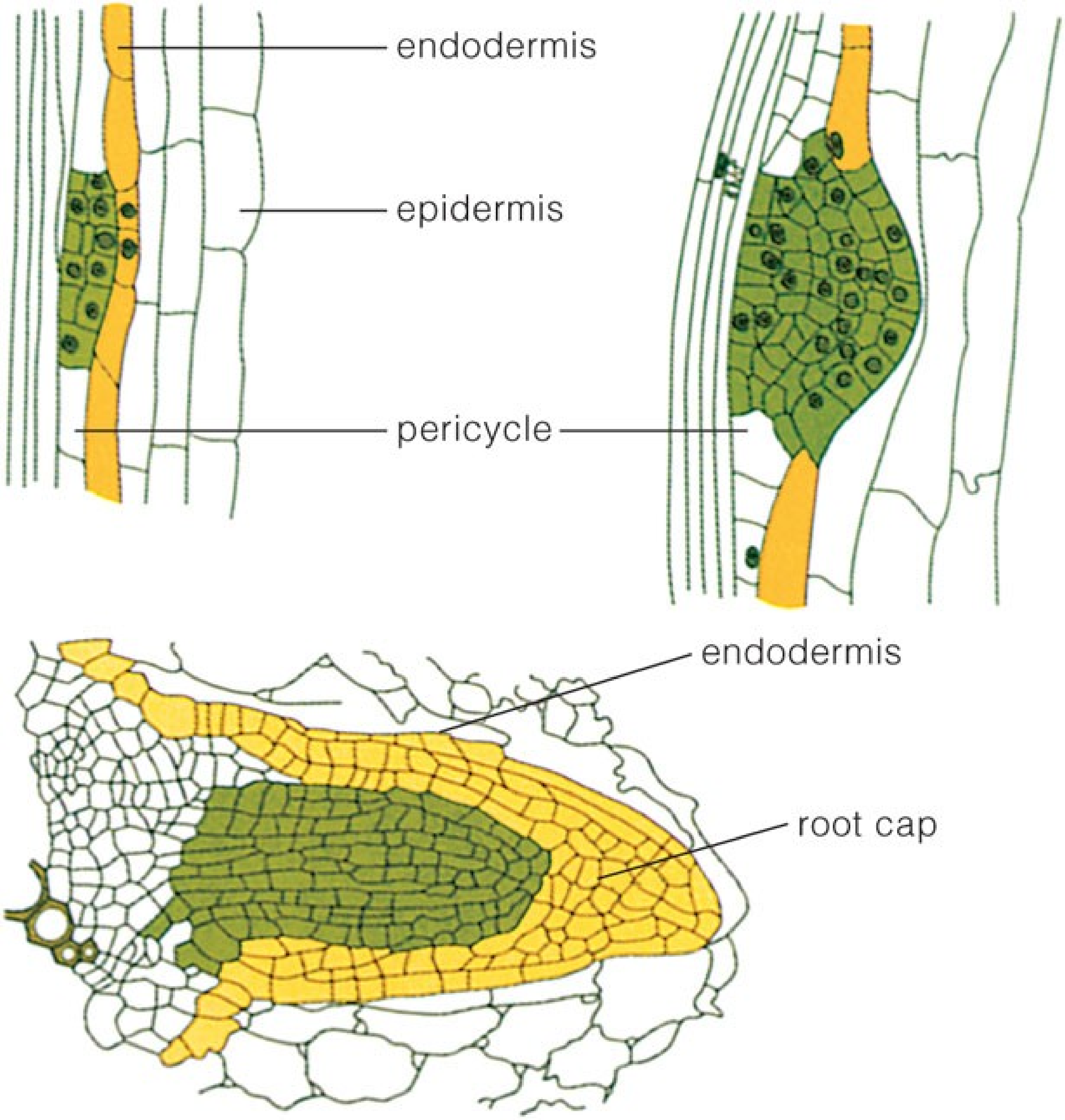
Pericycle

- Long-lived parenchyma cells served as half-meristem
- Initiates development of lateral roots
- Contributes to vascular cambium
- Contributes to cork cambium

Development of lateral roots



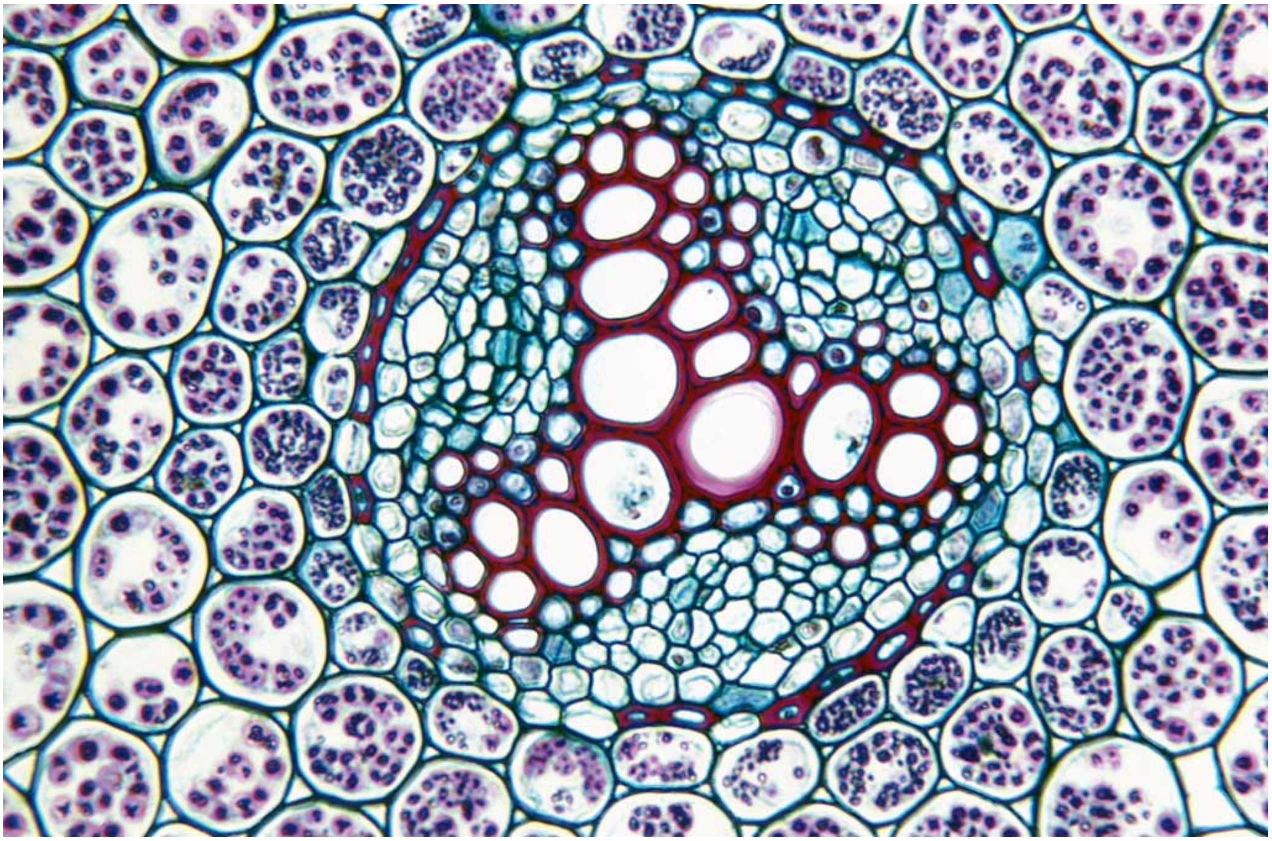
Development of lateral roots (step by step)



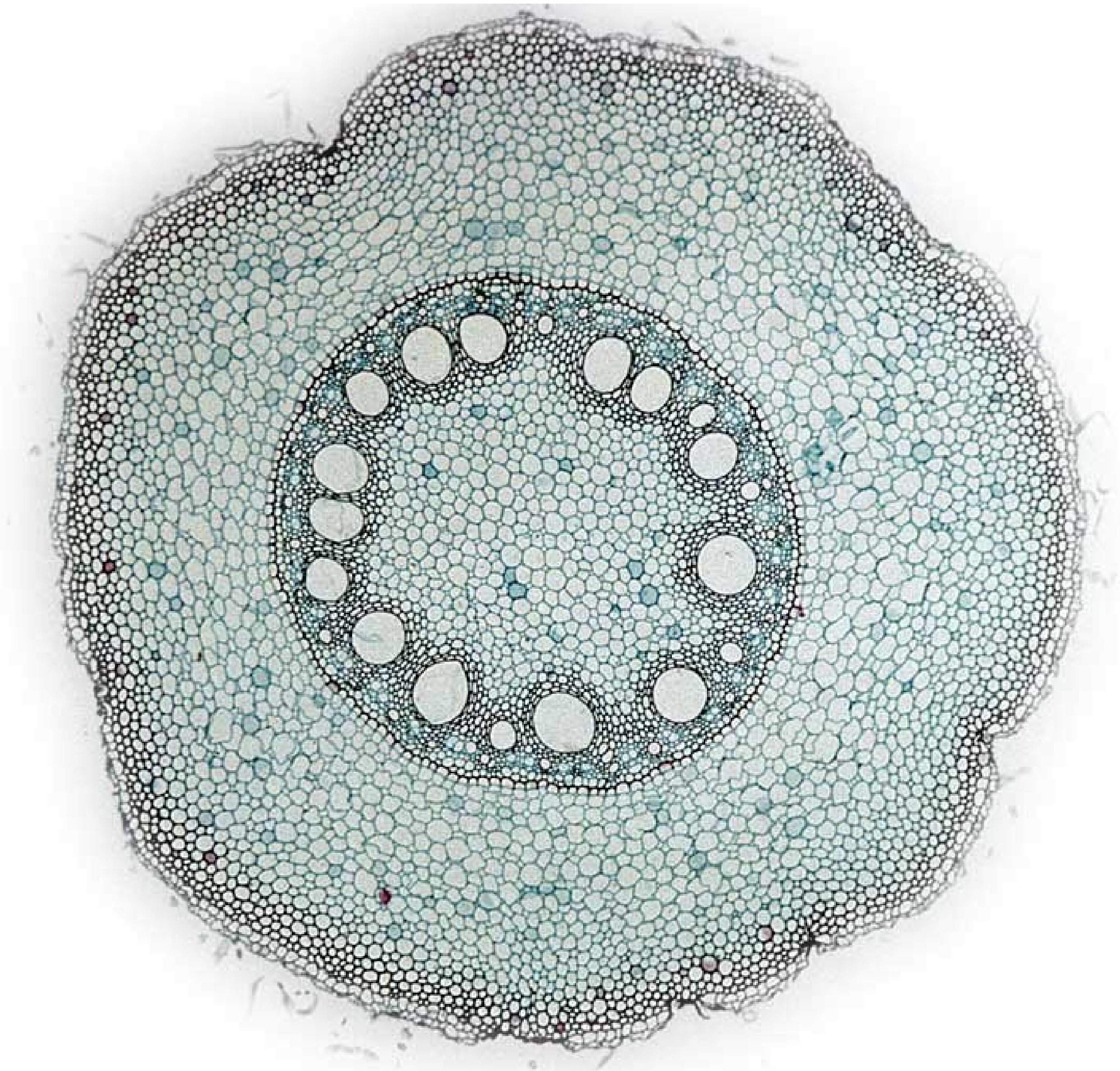
Vascular bundle

- Only one!
- Has radial (star-like) symmetry
- Xylem arranged in rays, multiple in monocots, 2-4 in other plants

Radial structure of root vascular bundle in buttercup (*Ranunculus* sp.)

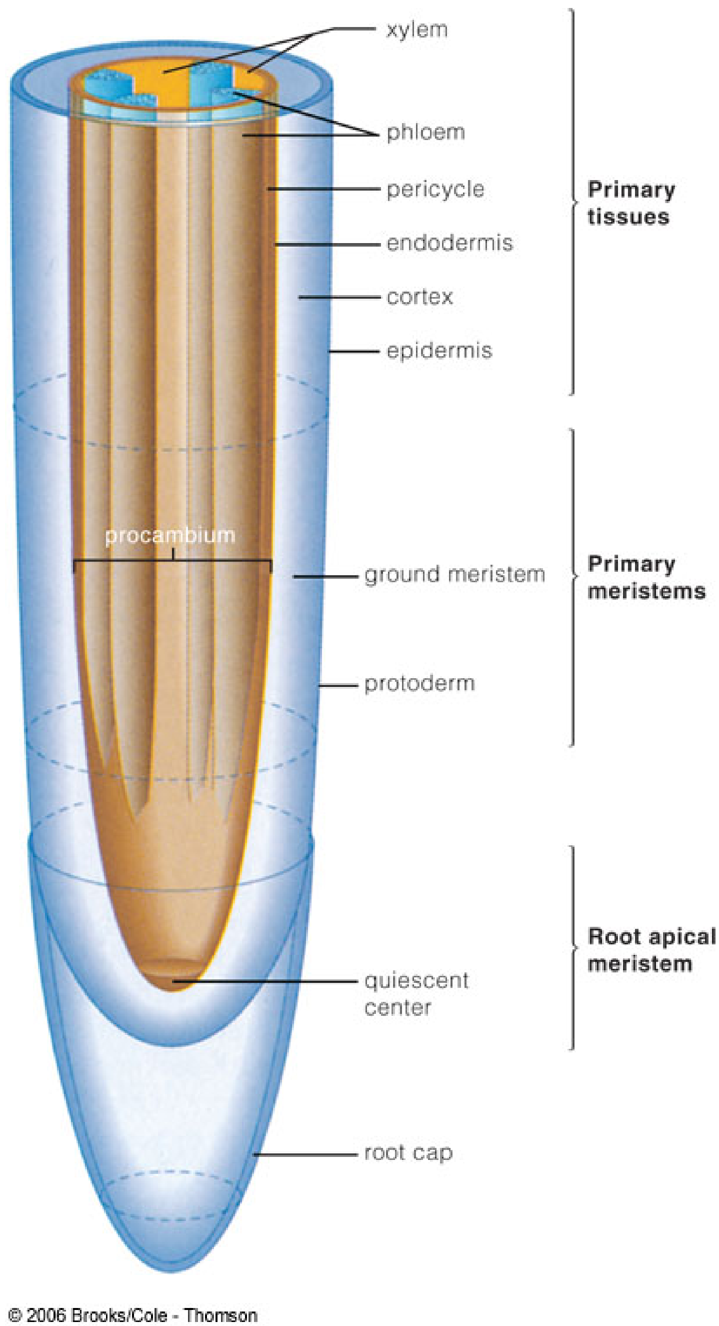


Root of monocot (*Zea mays*



45.4 Origins of root tissues

Development of tissues



In essence, development of tissues in root is analogous to stem.

45.5 Water transport in roots

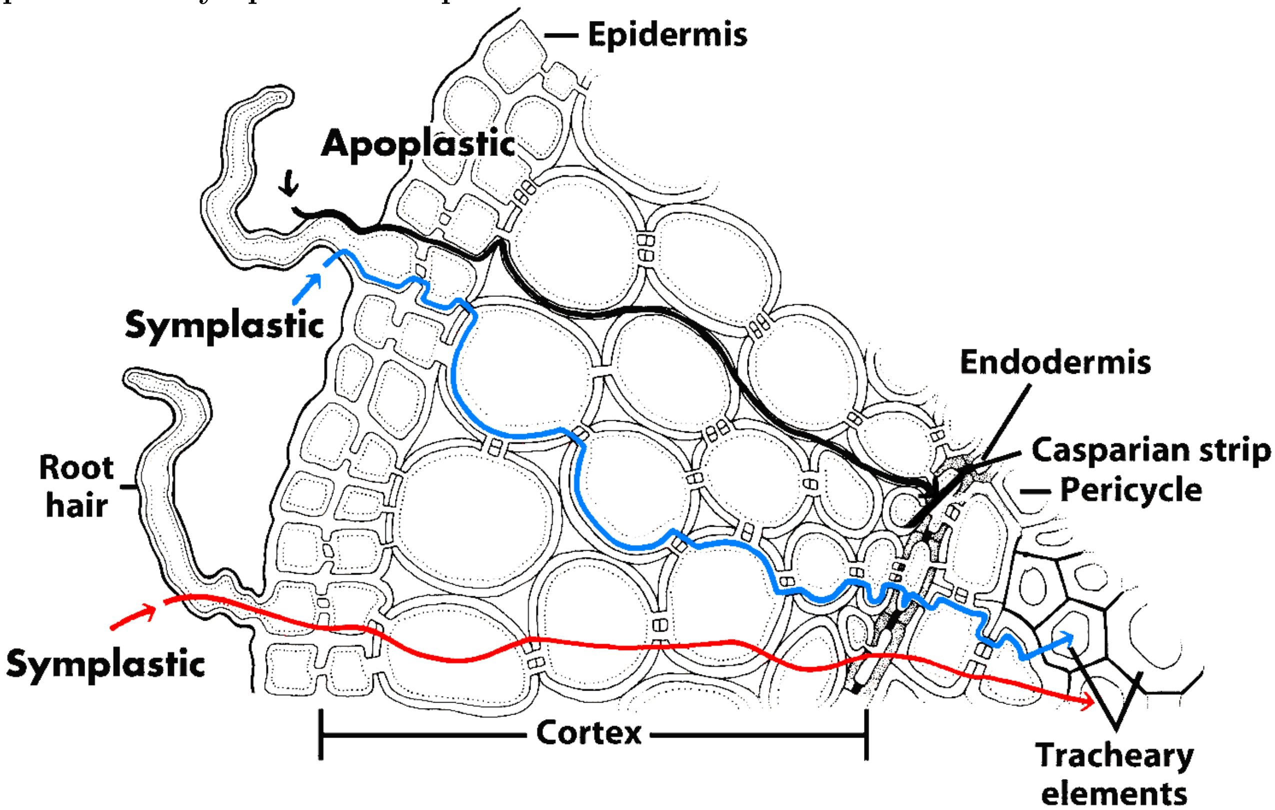
Rhizodermis and osmosis

- The existence of root hairs dramatically increases the surface of absorption
- Every root hair cell increase the internal concentration of large molecules, typically organic acids
- Process of concentration requires ATP
- As a result, osmosis water flow starts from soil to root cells

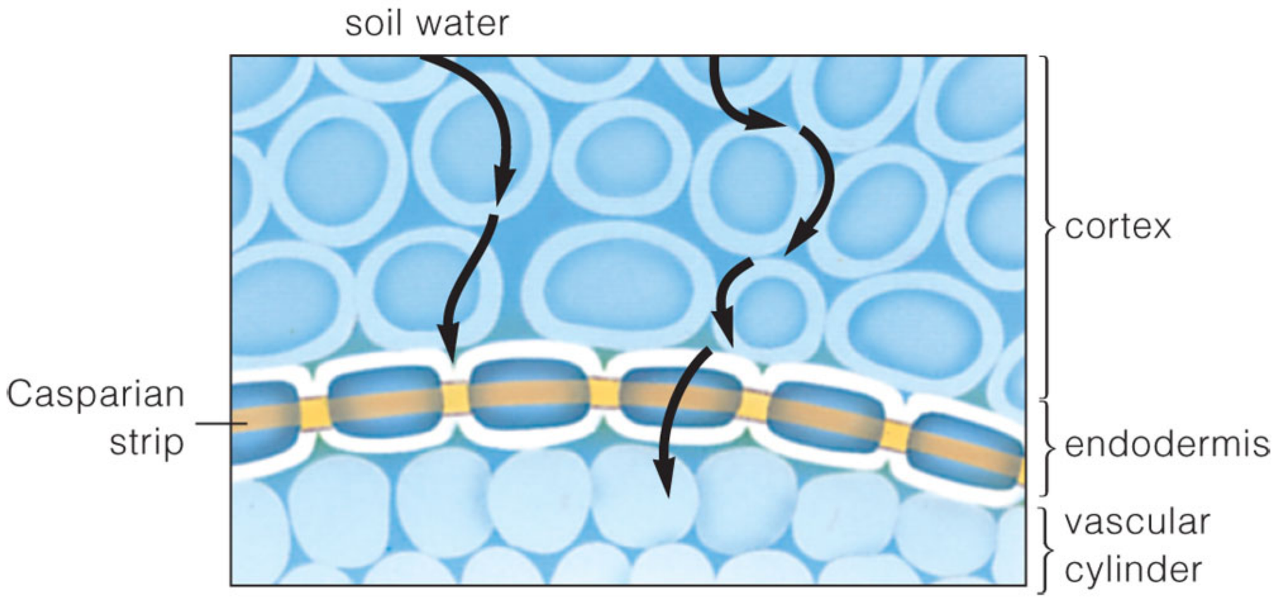
Endodermis and root pressure

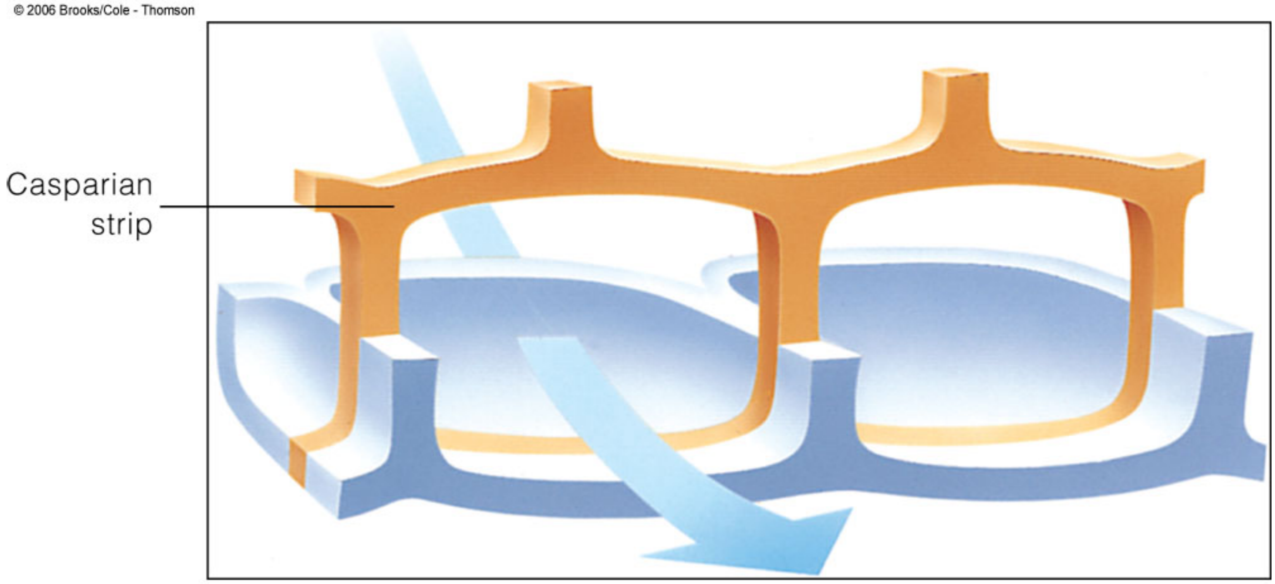
- From rhizodermis to endodermis, transport of water is both symplastic and apoplastic
- In the endodermis cells, Caspari stripes stop apoplastic transport and therefore forced symplastic transport
- This is a high-energetic process requires ATP
- As a result, water will be pushed up from root: this is the root pressure

Apoplastic and symplastic transport in the root

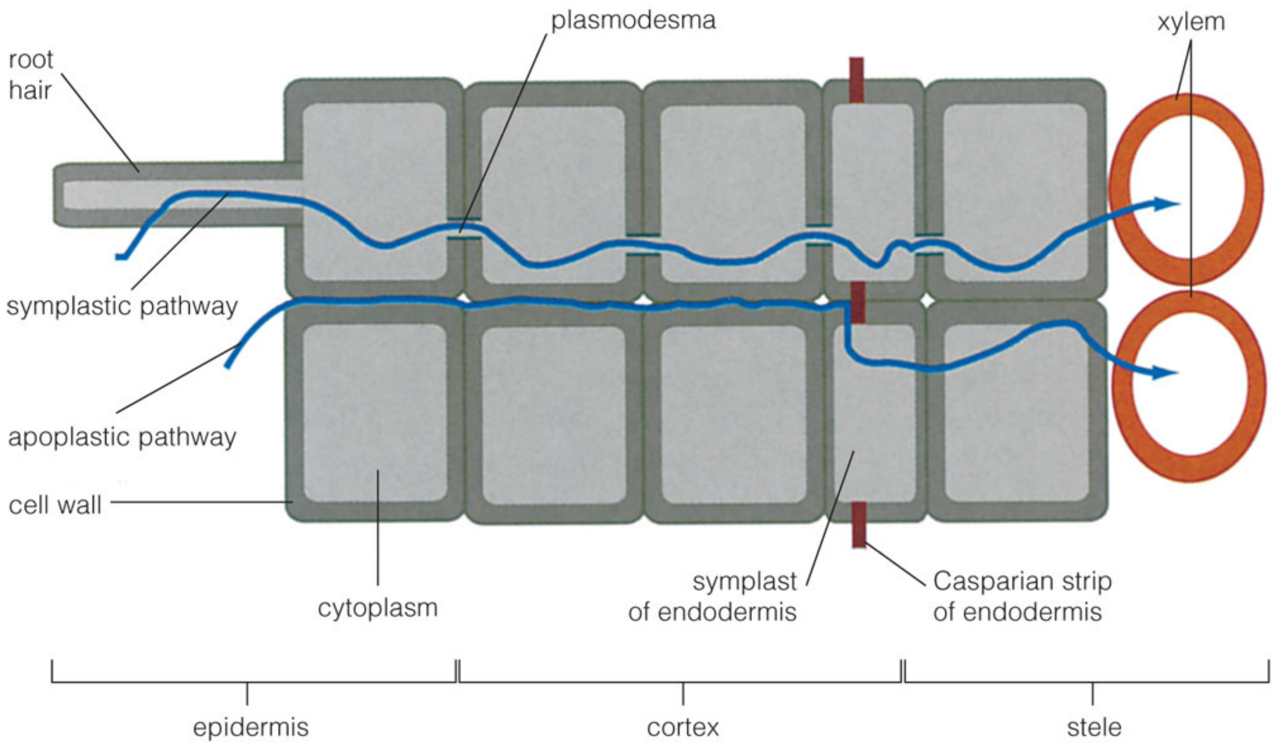


Casparian strips

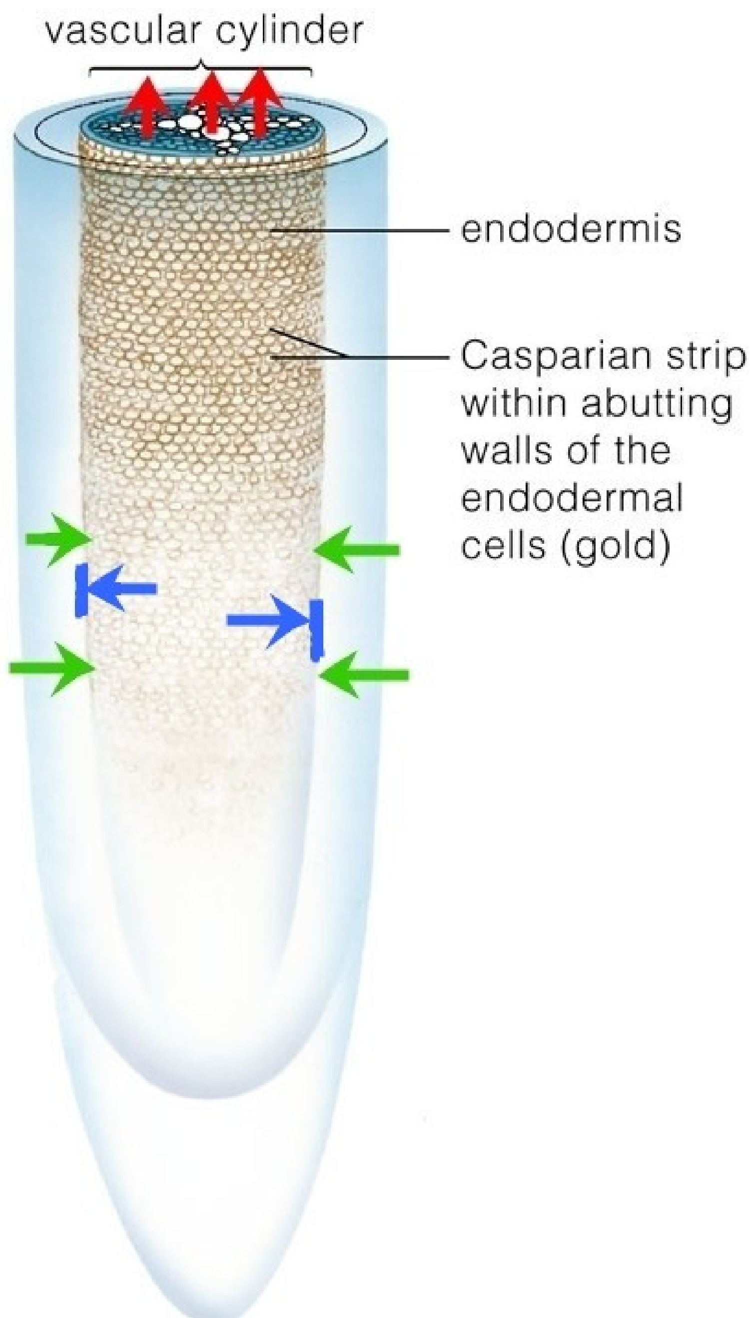




How Casparian strips are working



Origin of root pressure



Water flow in plants

- Plants need water:
  - To supply photosynthesis
  - To cool via transpiration
  - To obtain required minerals
- Water flows because of:
  - Root pressure
  - Capillarity force
  - Transpiration "suction"

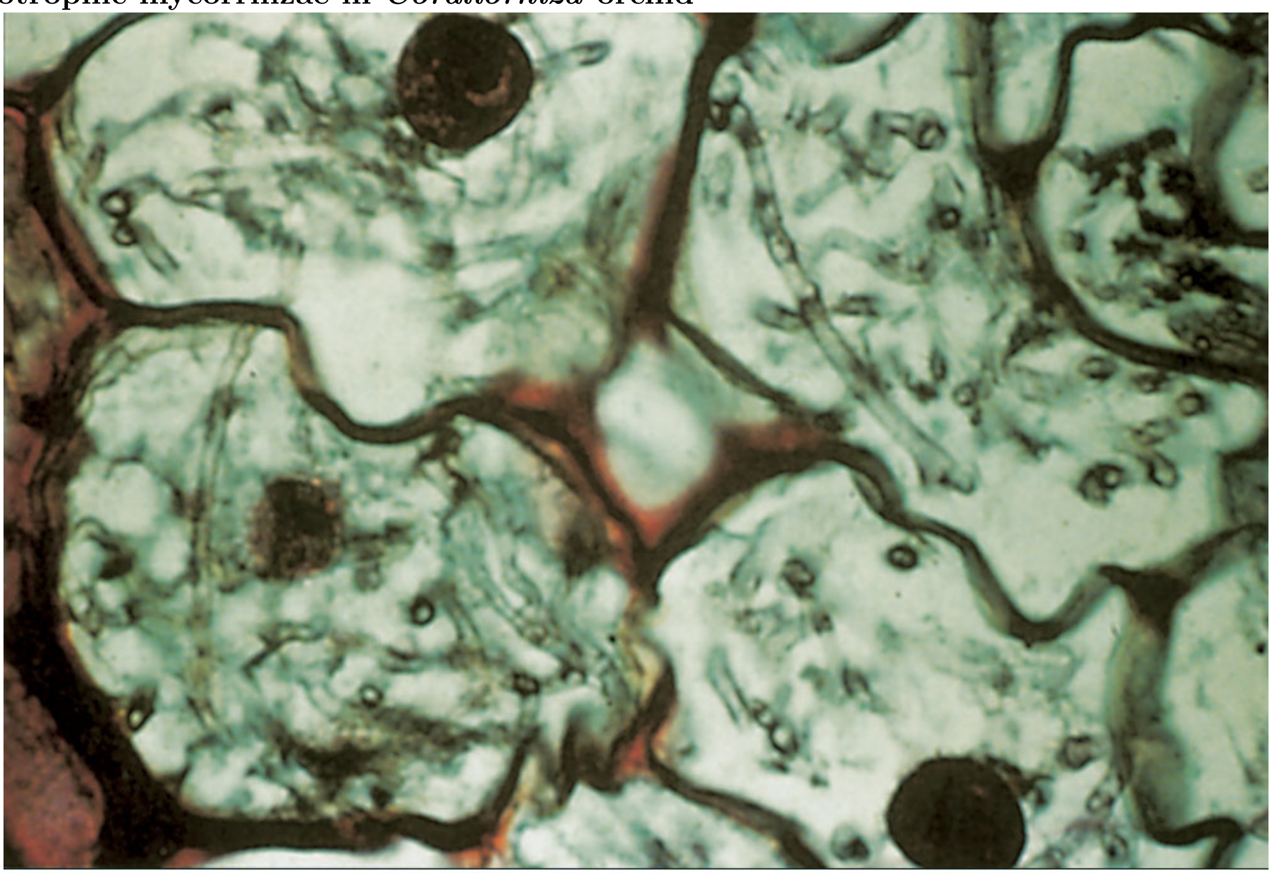
45.6 Diversity of roots

Modifications of roots

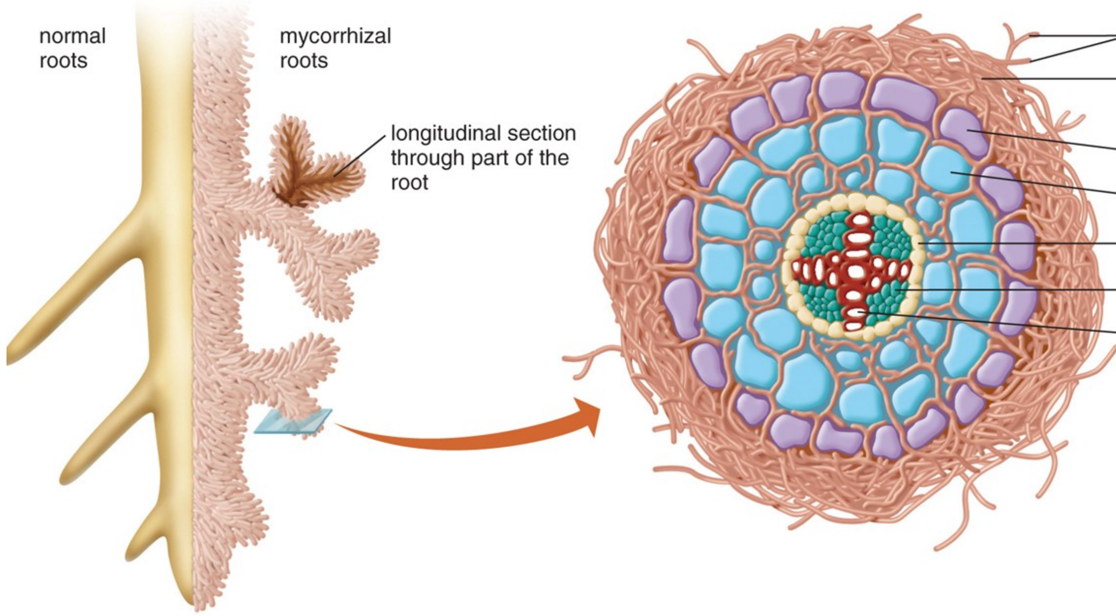
- Adventive buds with root origin (many plants)
- Mycorrhizae: endotrophic (grasses, orchids) and ectotrophic (trees)
- Haustoria (parasites like Cuscuta—dodder plant)
- Root nodules (legumes, Fabaceae family)
- Contractile roots (*Hyacinthus* spp.—hyacynth, *Taraxacum* spp.—dandelion)
- Storage roots (*Daucus carota*—carrot, *Armoracia officinalis*—horseradish)
- Supportive roots (many tropical plants)
- Defensive, spiny roots (ivy)
- Photosynthetic roots (some orchids)

45.7 Diversity of roots

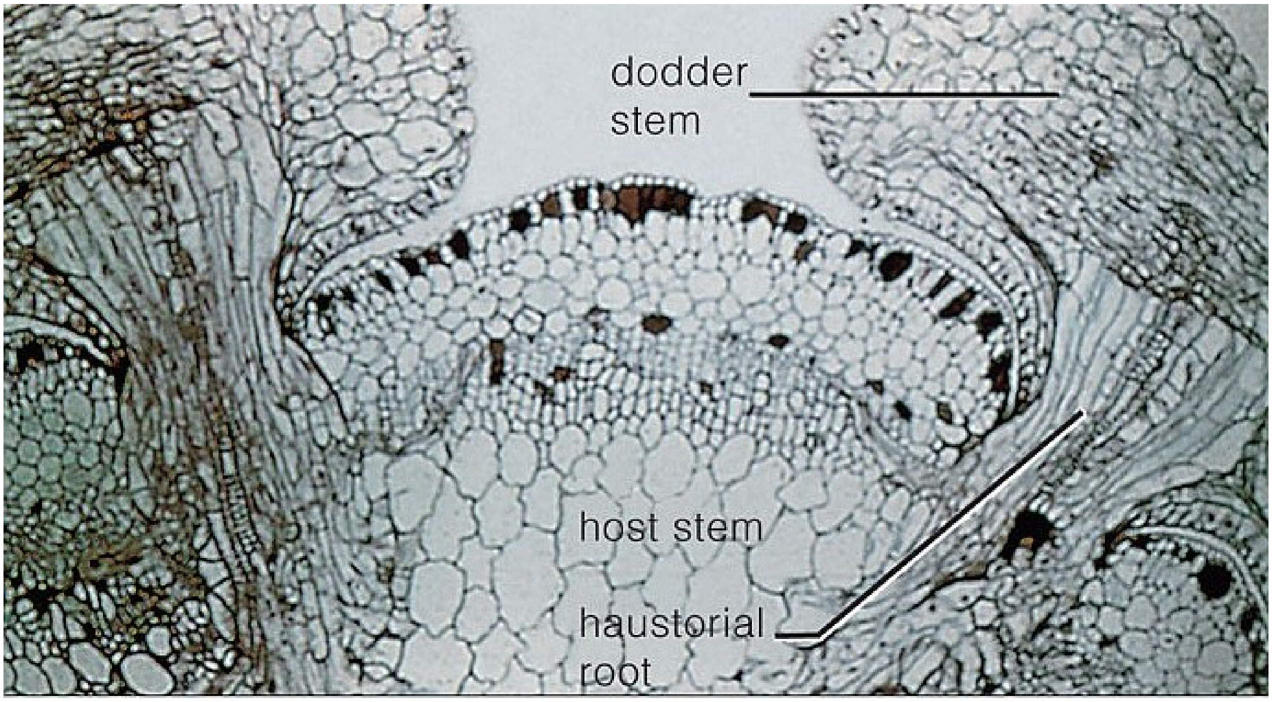
Endotrophic mycorrhizae in *Corallorhiza* orchid



Ectotrophic mycorrhizae of trees



Haustoria of *Cuscuta* (dodder)



Nodulated roots of soybean (*Glycine max*)

Contractile roots of *Hyacinthus orientalis*

Supportive roots of mangrove plants

Supportive roots of *Pandanus* sp.

Defensive spiny roots of ivy (*Hedera* sp.)

Photosynthetic aerial roots of orchids

Table of modifications

Function	Stem	Leaf	Root
Expansion	...	Plantets	Adventive buds
Storage	...	Succulent leaves	Storage roots
Photosynthesis	...	DEFAULT	Some aerial roots
Defense	...	Spines, scale	Root spines
Support	DEFAULT	Leaf tendrils	Aerial and contractile roots
Interactions	...	Traps, "sticky tapes", urns	Mycorrhizae, haustoria, nodulated roots

Summary

- Vascular tissues of root is a modified protostele or solenostele (in monocots).

- Root hairs, Casparian strips, capillarity and transpiration work together to make water flow in plant.
- Root-related part of water flow is the **root pressure**.
- Roots have not less modifications than leaves.

For Further Reading

References

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

Outline

46 Plant diversity

46.1 Systematics

Basics of systematics

Terms covered:

- Systematics = taxonomy
- Species, taxonomic hierarchy
- Taxon, rank = category, classification
- Kingdom, phylum, class, order, family, genus, species
- Subclass, subfamily and other intermediate ranks
- Subspecies and cultivars

Biological nomenclature

Terms covered:

- Binomial name, species epithet, reference = citation
- Synonyms, priority (older names have preference), starting dates (1753 for plants)

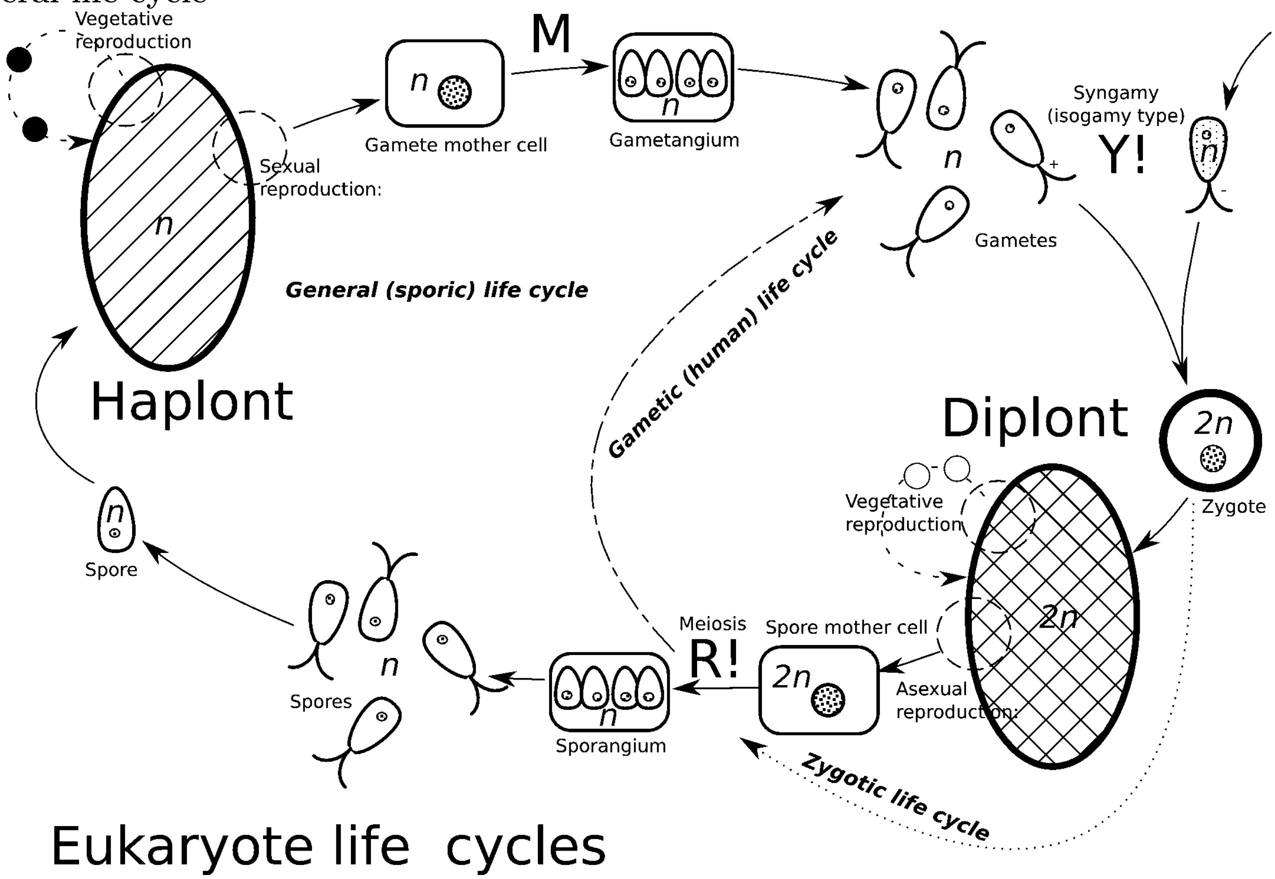
Examples

		Example 1	Example 2
Kingdom	Regnum	Vegetabilia	Animalia
Phylum	Phylum	Spermatophyta	Chordata
Class	Classis	Angiospermae (Magnoliopsida)	Mammalia
Order	Ordo	Liliales	Primates
Family	Familia	Asparagaceae	Hominidae
Genus	Genus	*Chlorophytum*	*Homo*
Species	Species	*Chlorophytum comosum* (Thunb.) Jacq. 1862	*Homo sapiens* L.

$$\overbrace{\underbrace{\text{Chlorophytum}}_{\textit{Genus name}}\quad \underbrace{\text{comosum}}_{\textit{Species epithet}}\quad \underbrace{\text{(Thunb.)}}_{\textit{First author}}\quad \underbrace{\text{Jacq.}}_{\textit{Second author}}\quad \underbrace{\text{1862}}_{\textit{Year of description}}}^{\textit{Species name}}$$

46.2 Kingdom Vegetabilia, land plants

General life cycle

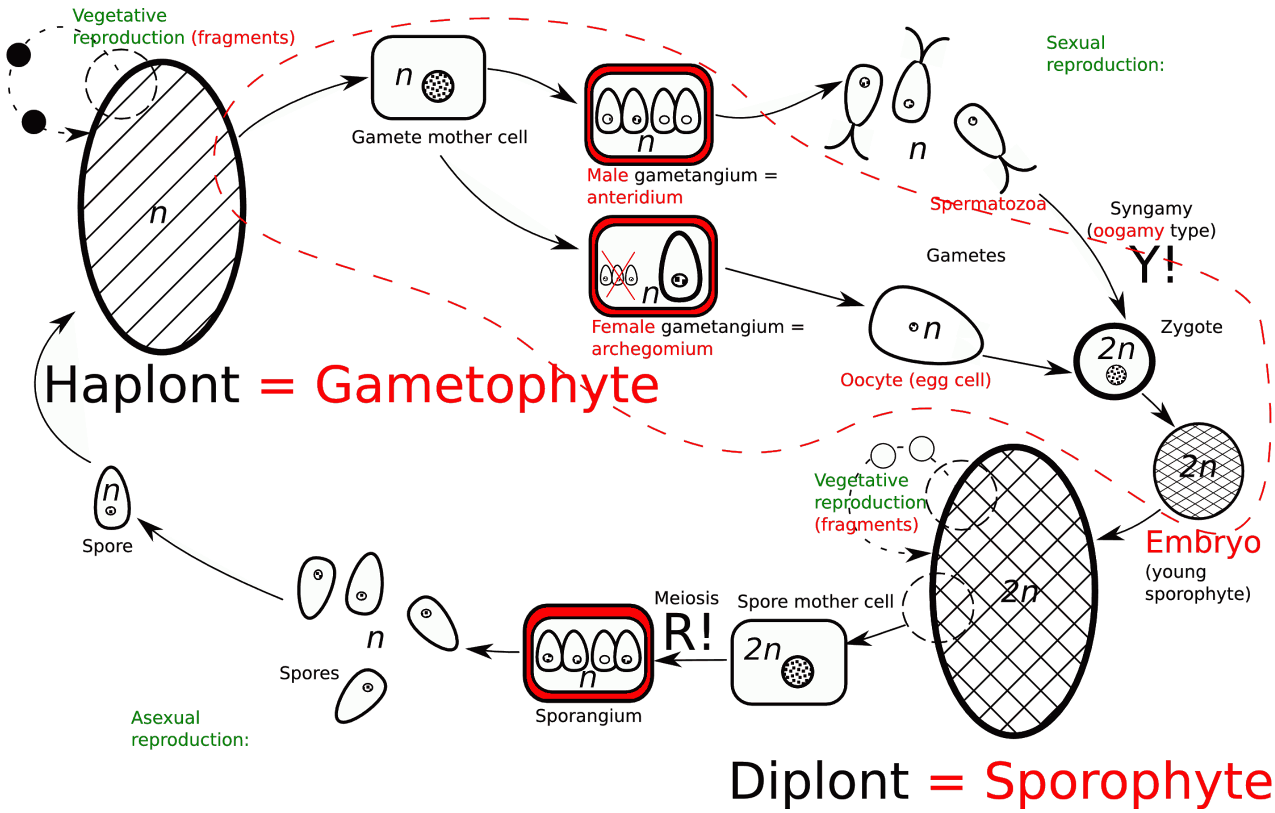


Life cycle of land plants

Terms covered:

- Sporophyte and gametophyte
- Gametangia: archegonium and antheridium
- Spermatozoa and oocyte (egg cell)
- Embryo and parasitic sporophyte
- Predominance of sporophyte or gametophyte

Life cycle of land plants: differences



47 Kingdom Vegetabilia, land plants

47.1 Mosses

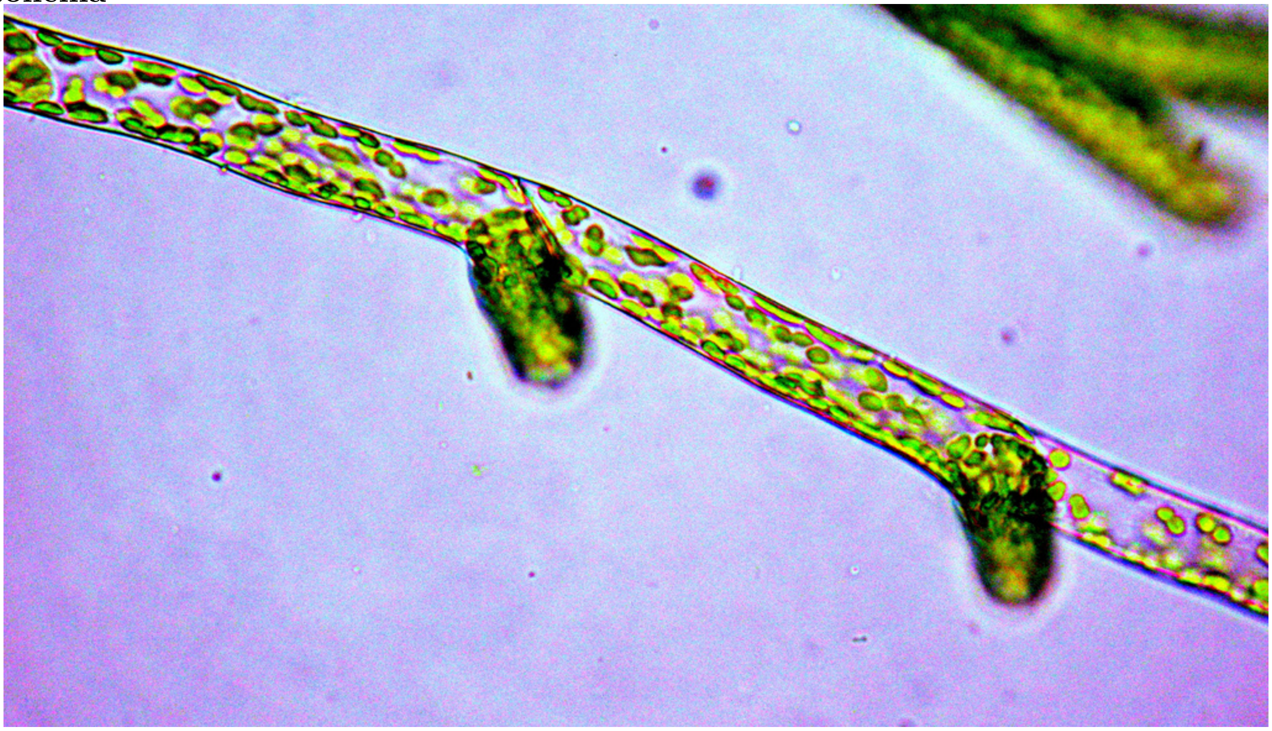
Three main phyla

- **Bryophyta**: gametophyte predominance
- **Pteridophyta**: sporophyte predominance, no seed
- **Spermatophyta**: sporophyte predominance, seed

Bryophyta

- $\approx 20,000$ species
- Sporic life cycle with gametophyte predominance
- Sporophyte reduced to sporogon (sporangium with seta), usually achlorophyllous, parasitic
- No roots, only rhizoid cells (long hairy dead cells capable for apoplastic transport)
- Poikilohydric plants
- Gametophyte starts development from protonema

Protonema



Life cycle of mosses
Covers: sporogon, biflagellate spermatozoa, the conflict between water cross-fertilization and wind distribution of spores which may be considered as "evolutionary dead end".

Three main kinds (subphyla) of mosses

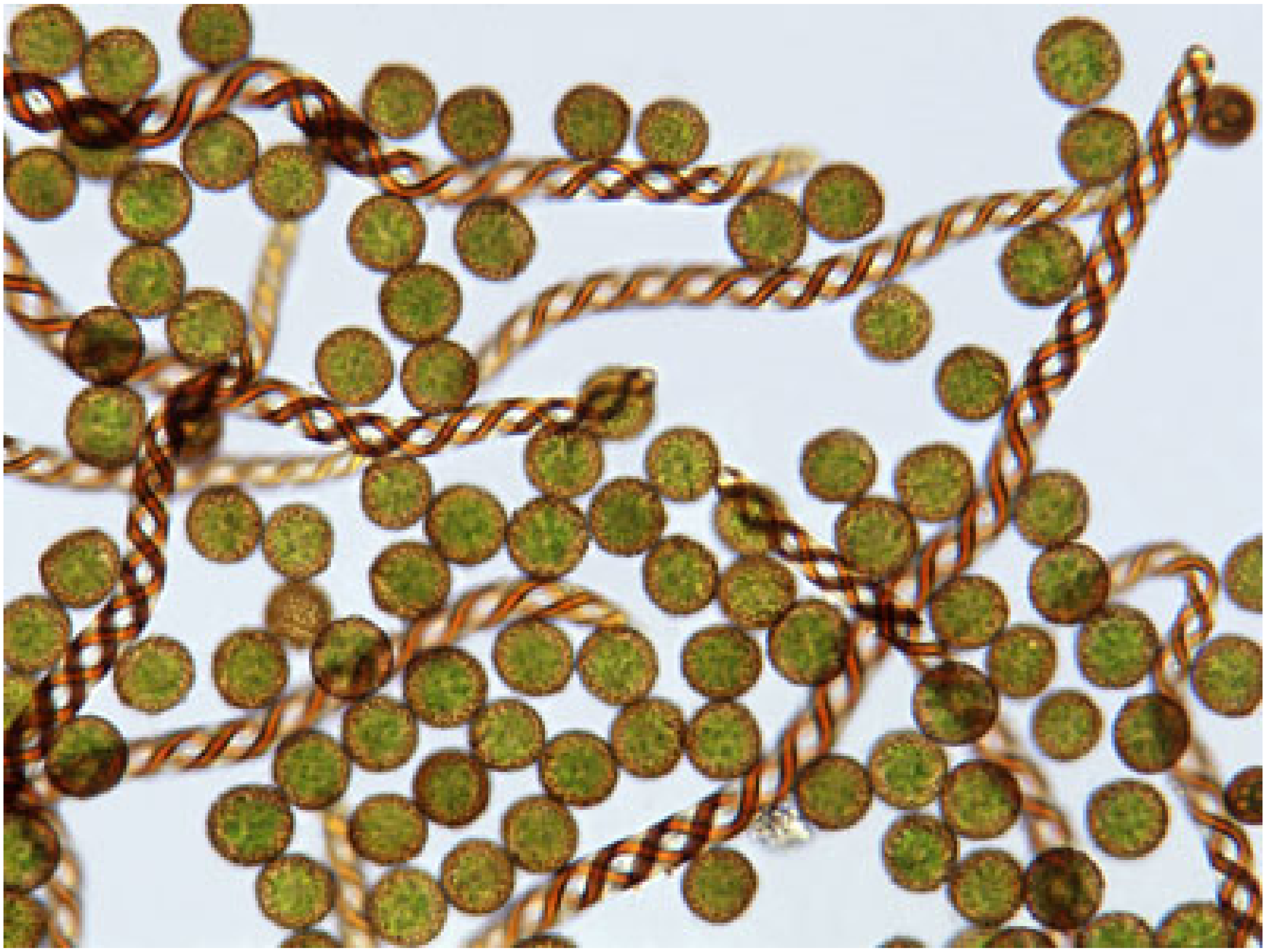
- **Hepaticae**—liverworts. Three classes, most primitive are Haplomitriopsida. Body leafy or thalloid, usually has dorsal and ventral parts, sporogon bag-like, without columella, spores with elaters.
- **Bryophytina**—true mosses. Six classes, most important are Sphagnopsida (peat mosses), Polytrichopsida (haircap mosses) and Bryopsida. Body radial, sporogon long, with columella, spores without elaters.
- **Anthocerotophytina**—hornworts. One class. Body flattened (thallus), sporogon long, green, sometimes branched, with columella and stomata, spores with elaters.

Mosses in the "evolutionary dead end"

- They resolved "skyscrapers problem" via gametophyte, not sporophyte
- Gametophyte needs water fertilization, which restricts the size and also requires the dense growing
- Also, root system is absent: this is an additional size restriction
- If sexual organs appear on the bottom of leafy shoot, sporogon (sporophyte) could not distribute spores with a wind
- The only way out is to "start over" from thallus and make sporophyte (which was highly specialized for the spore distribution) a main stage and reduce gametophyte

***Haplomitrium gibbsiae*, primitive liverwort**

Elaters of liverworts (*Lepidozia* sp.)



***Sphagnum* sp. (Bryophyta, Sphagnopsida) with sporogons**

Dawsonia superba **(Bryophyta, Polytrichopsida)—the largest moss with vascular system**

Bryum capillare **(Bryophyta, Bryopsida)**

Leiosporoceros dussii **(Bryophyta, Anthocerotopsida)—primitive hornwort**

47.2 Ferns

Pteridophyta: ferns and allies

- $\approx 12,000$ species and six classes
- Sporic life cycle with sporophyte predominance
- Gametophyte is often reduced to **prothallium** (small hornwort-like plant), some Pteridophyta have male and female gametophytes
- Have true roots (only whisk ferns, Psilotopsida are exception)
- Homoiohydric plants (same as seed plants)
- Sporophyte always starts development from embryo located on gametophyte
- Have true xylem and phloem, but do not have secondary thickening (exceptions: fossils and extant *Isoëtes* and *Botrychium*)

Pteridophyta classes

- Subphylum Lycopodiophytina (lycophytes)
  - Class **Lycopodiopsida**
- Subphylum Pteridophytina (monilophytes)

– Class **Equisetopsida** (horsetails)
– Class **Psilotopsida** (whisk ferns)
– Class **Ophioglossopsida** (ophioglossalean ferns)
– Class **Marattiopsida** (giant, or marattialean ferns)
– Class **Pteridopsida** ("true" ferns)

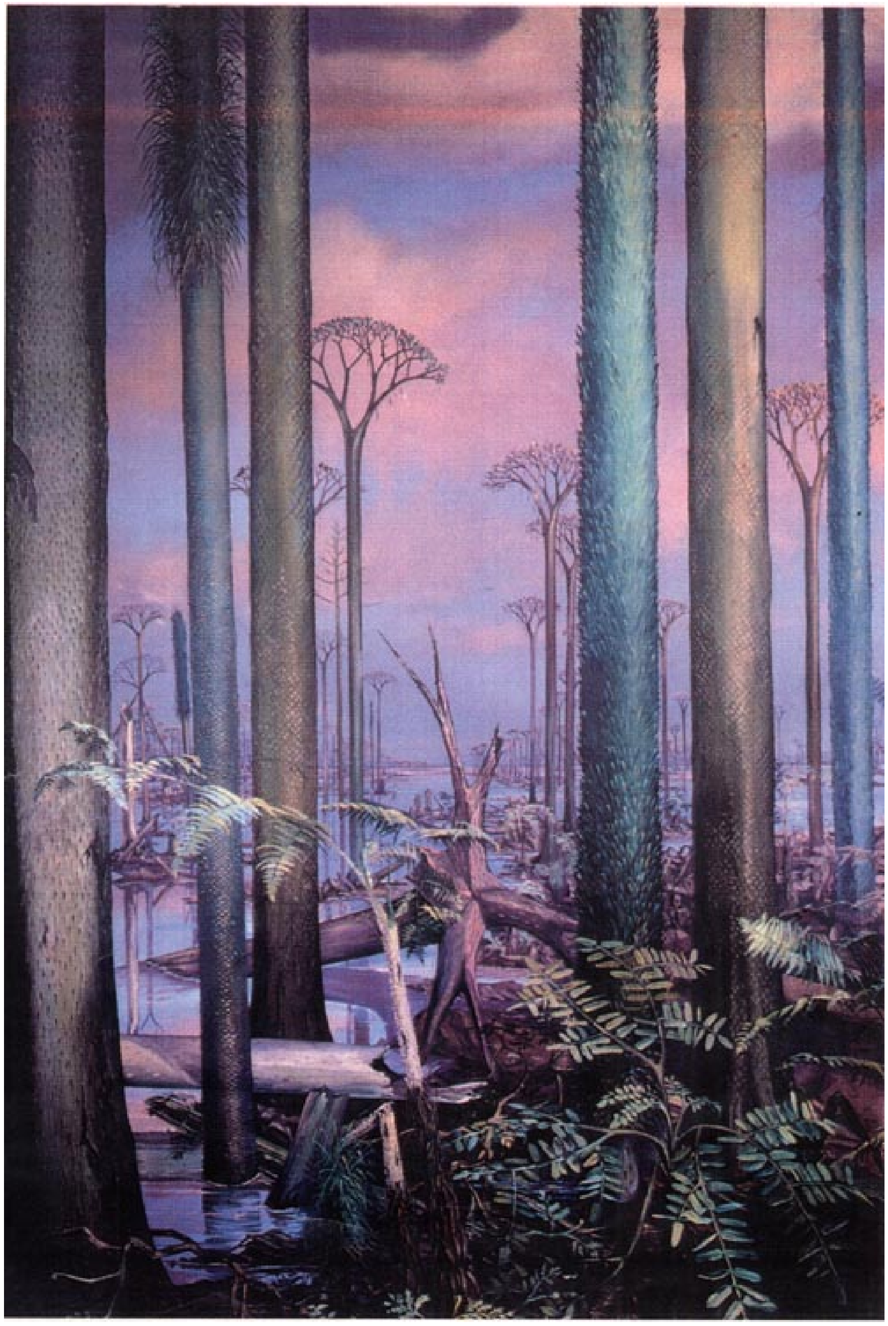
Lycopodiopsida

- Four main genera (*Huperzia*, *Lycopodium*, *Selaginella* and *Isoëtes*) and $\approx$ 1000 species
- Separate, **microphyllous*** lineage of Pteridophyta (all other groups are **megaphyllous**)
- Sporangia associated with leaves and often form **strobilus***. Spermatozoon typically with two flagella (like in mosses). Homosporous genera have achlorophyllous, mycoparasitic underground gametophyte.
- In the past, were dominant trees of Carboniferous tropical swamp forests (lepidodendrids) and their remains became a coal
- Two genera, *Selaginella* (spike moss) and *Isoëtes* (quillwort) are heterosporous.

Tropical lycophyte, *Huperzia linifolia*

***Phylloglossum drummondii*, one of smallest lycophytes**

Before: Chicago 300 Million Years Ago (lepidodendrids)



After: quillwort, aquatic lycophyte *Isoëtes* sp.

Pteridophyta classes

- Subphylum Lycopodiophytina (lycophytes)
  [Microphyllous]
  - Class **Lycopodiopsida**
- Subphylum Pteridophytina (monilophytes)
  [Megaphyllous]
  - Class **Equisetopsida** (horsetails)
  - Class **Psilotopsida** (whisk ferns)
  - Class **Ophioglossopsida** (ophioglossalean ferns)

– Class **Marattiopsida** (giant, or marattialean ferns)
– Class **Pteridopsida** ("true" ferns)

47.3 Classis Equsetopsida, horsetails

Equisetopsida

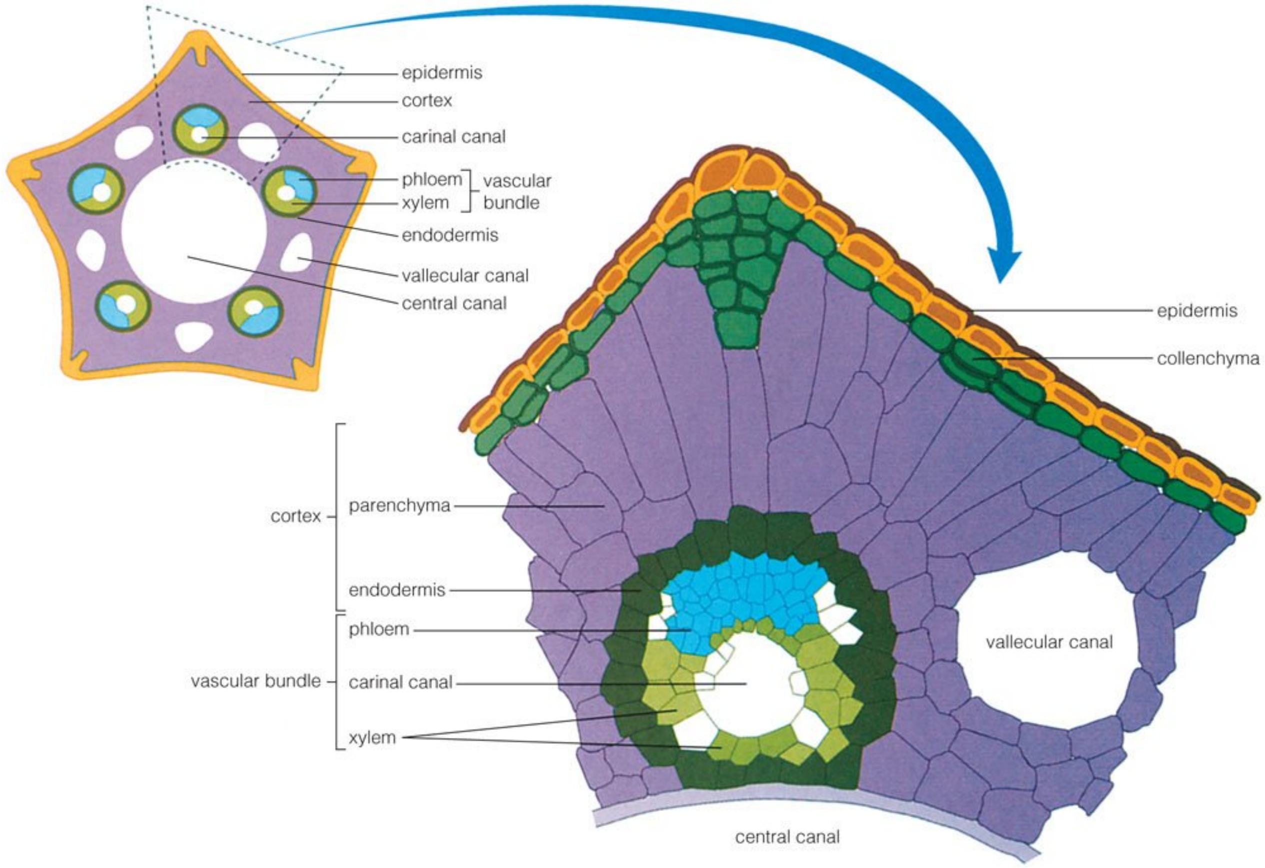
- Small group of one genus, *Equisetum* with ≈ 30 species
- Leaves are reduced into scales, stems are segmented, photosynthetic. Have specific stele—**artrostele** with specific central and peripheral canals (similar to stele of some grasses)
- Sporangia associated with specialized leaves—sporangiophores. Spores have attached **elaters**. Gametophyte minute, usually dioecious but plants are homosporous

Strobili and sporangiophores of *Equisetum arvense*

Equisetum giganteum

***Equisetum* sp. elaters**

Artrostele



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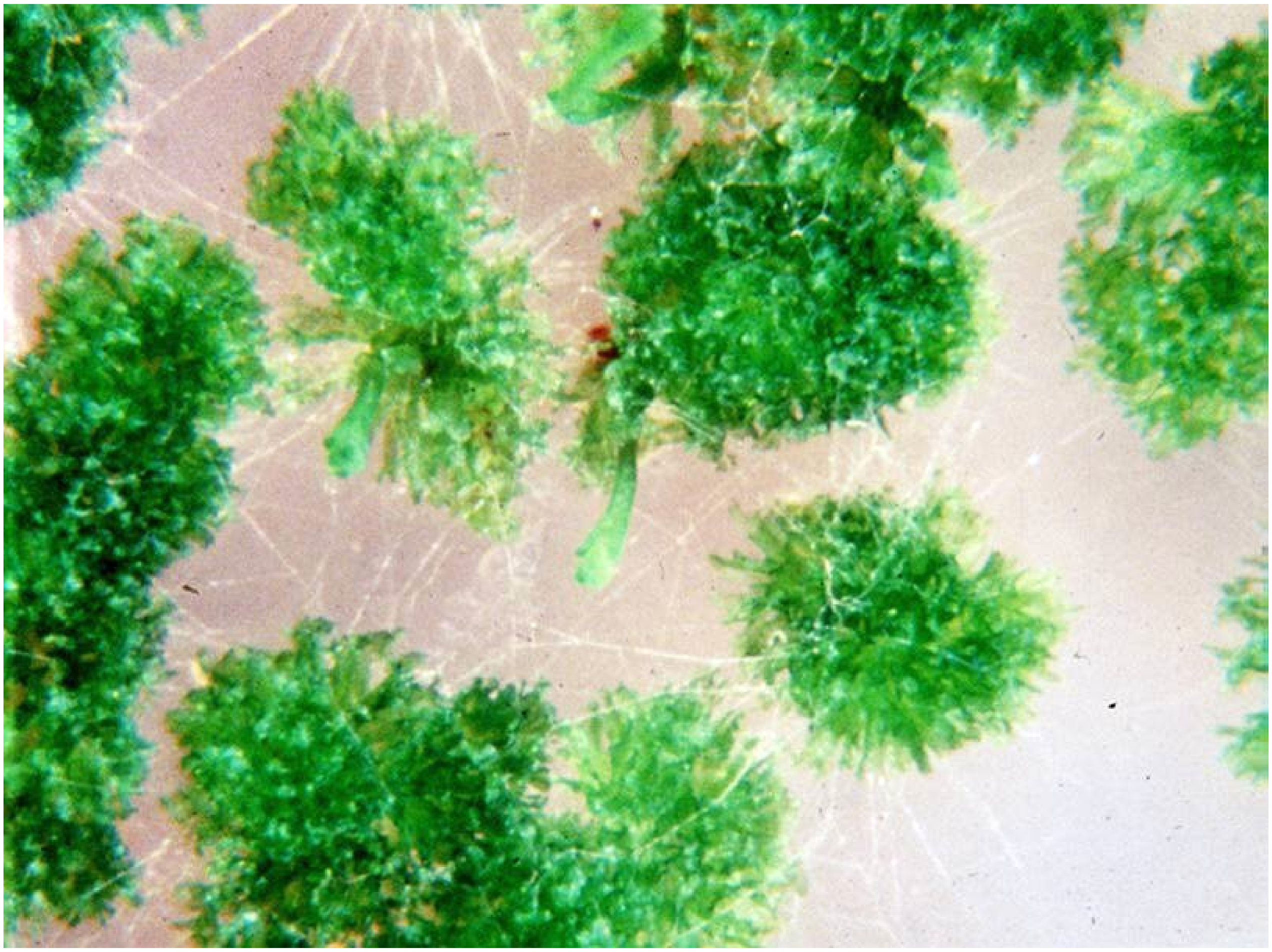
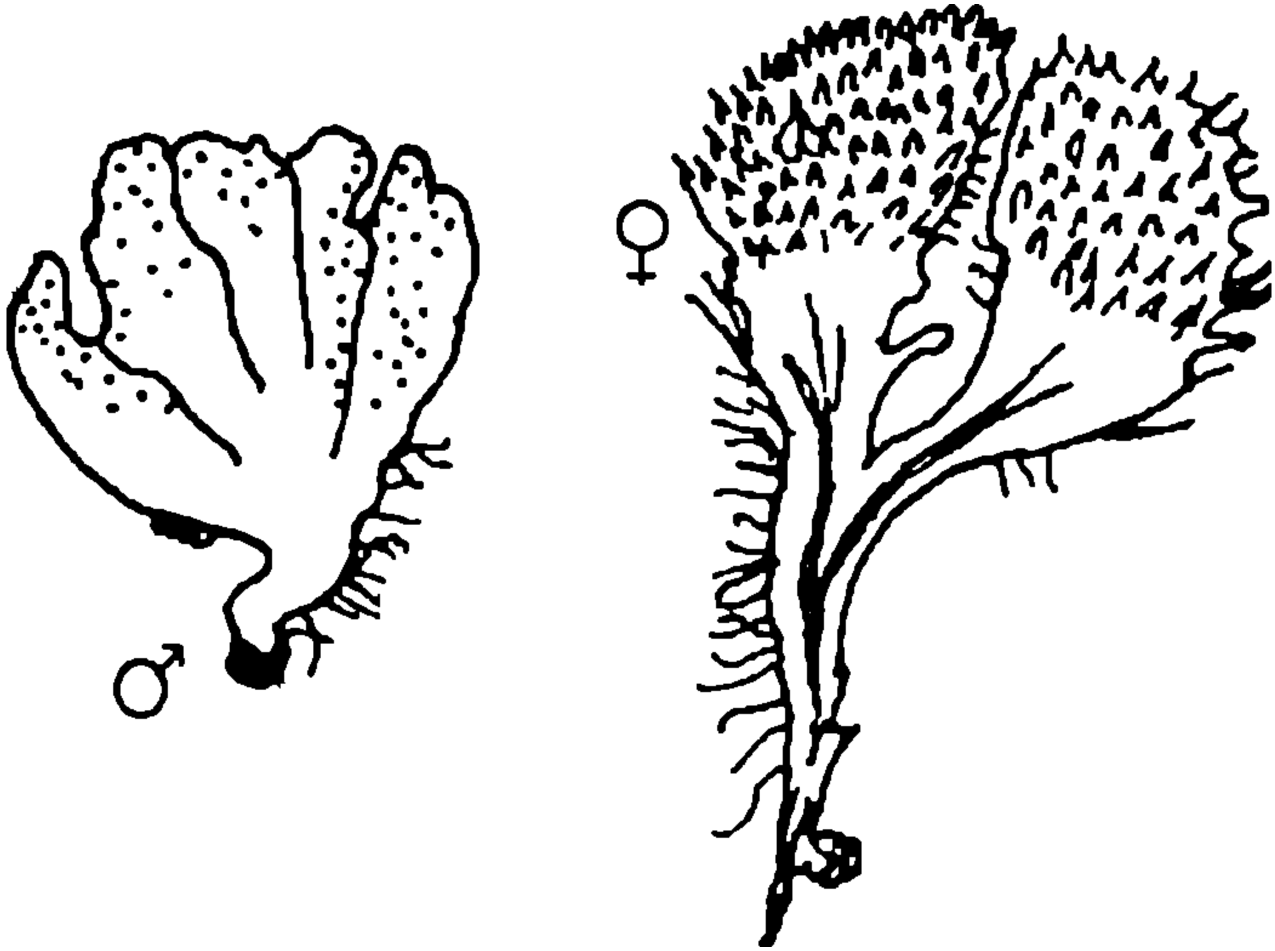
Horsetail gametophytes

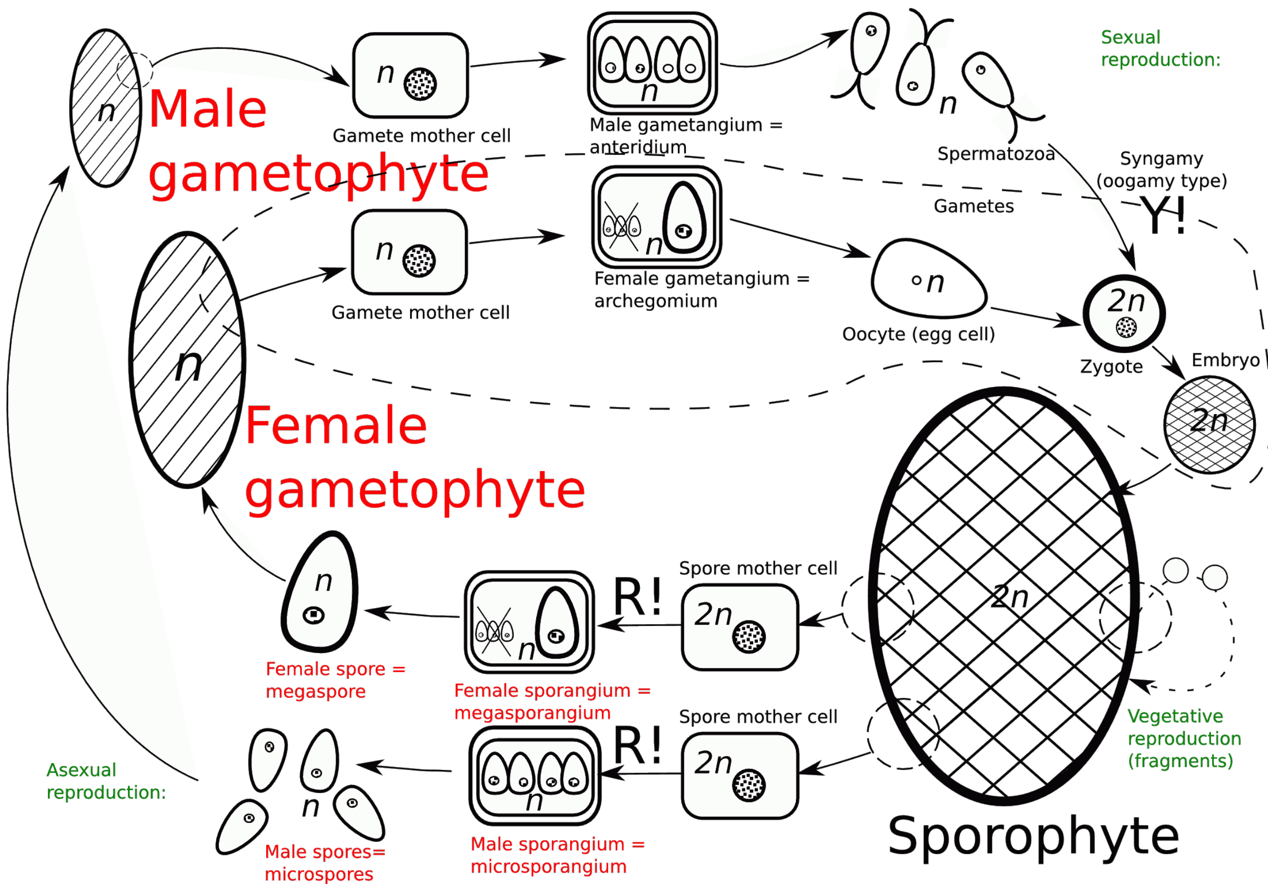


47.4 Heterospory

Horsetails start it: spores same, gametophytes different



Heterosporic cycle: differences



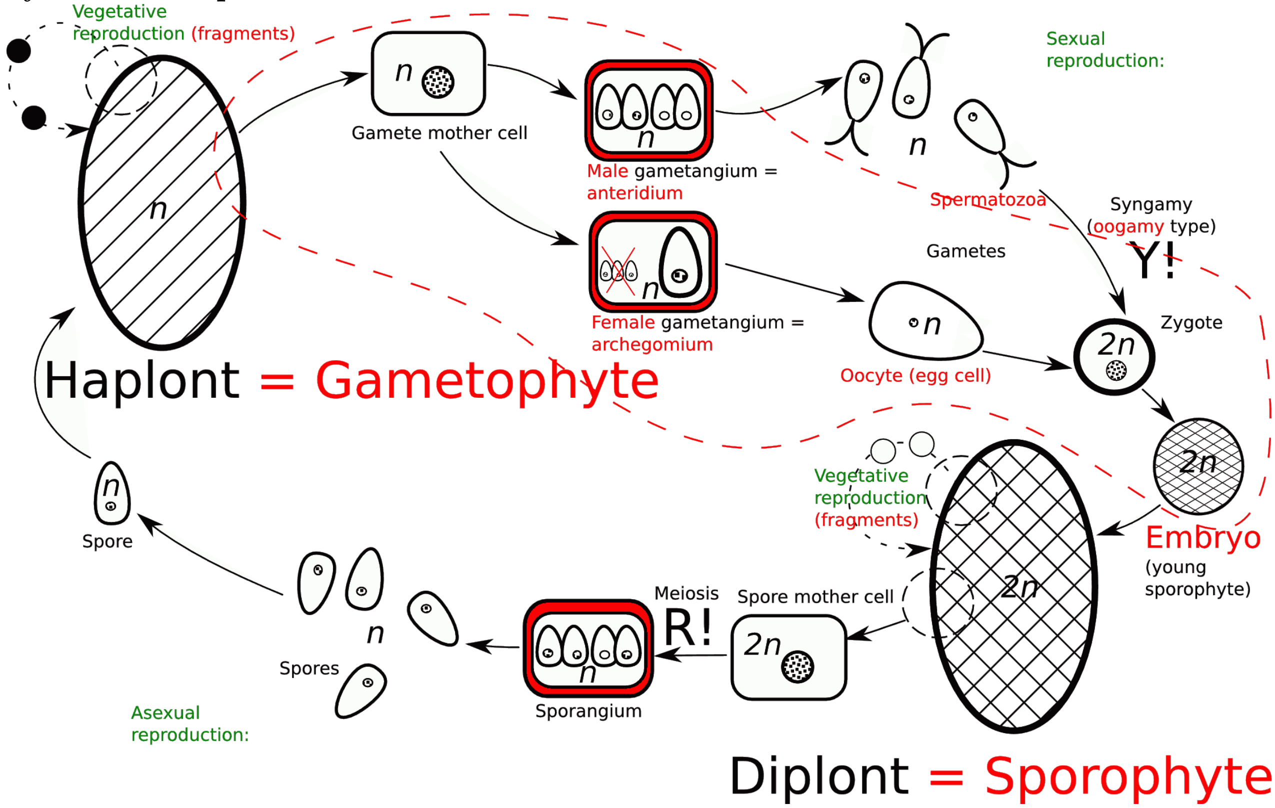
Heterospory

Heterosporous ferns (lycophytes *Selaginella* and *Isoëtes*, monilophytes *Salvinia*, *Marsilea*, *Pilularia*, *Regnellidium* and *Azolla*) went one step further and made their spores different too. It will allow the better allocation of resources and will restrict the self-fertilization.

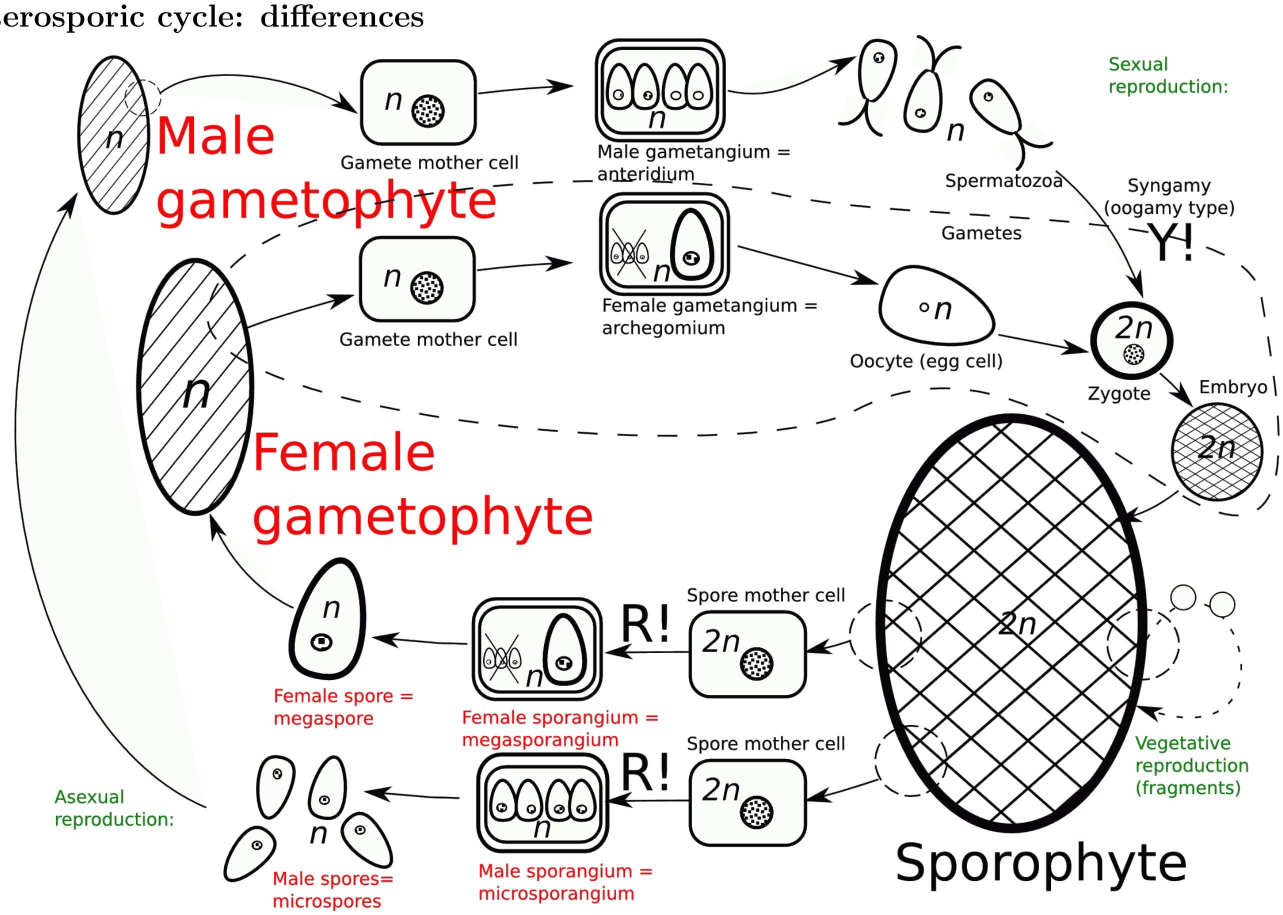
Terms covered:

- Male gametophyte, female gametophyte
- Microspores and microsporangium
- Megaspores and megasporangium

Life cycle of land plants



Heterosporic cycle: differences



47.5 More "ferny" ferns

Psilotopsida

- Small tropical group of two genera, *Psilotum* and *Tmesipteris* and 7 species
- Have protostele (like lycophytes), underground long-lived gametophytes but multiflagellate spermatozoa (like horsetails and all "higher" ferns). Sporangia unite into **synangia**. Leaves may absent (*Psilotum*) and replaced with **enatia**.
- Externally remain fossil **rhyniophytes**, the oldest extinct Pteridophyta

Hawaiian ***Psilotum complanatum***

New Zealand *Tmesipteris tannensis* with double synangium

Ophioglossopsida

- Small group (*Ophioglossum*, *Botrychium*, *Mankyua* and *Helminthostachys*) and ≈ 75 species
- Always have underground rhizome and aboveground bisected leaves: one half is the leaf blade and other half is **sporangiophore**. Gametophytes grow underground.
- Some (namely, *Botrychium*, grape fern) have **secondary thickening** of underground rhizome.
- *Ophioglossum vulgatum*, adder's tongue fern, has $2n = 1360$, the largest chromosome number ever.

***Ophiloglossum vulgatum*, $2n = 1360$ hero**

Helminthostachys zeylanicum **(Ophioglossopsida)**

Mankyua chejuense **(Ophioglossopsida)**

Marattiopsida

- Tropical ferns, several genera with $\approx$ 100 species
- Biggest ferns, one leaf (frond) could be 6 m length, but stems are smaller. Leaves with stipules.
- Sporangia (**eusporangia** like in all other Pteridophyta except "true" ferns) usually unite in **synangia**, gametophytes 1-2 cm in diameter, photosynthetic, terrestrial, usually long-lived.
- In a past, also were dominants of Carboniferous swamp forests.

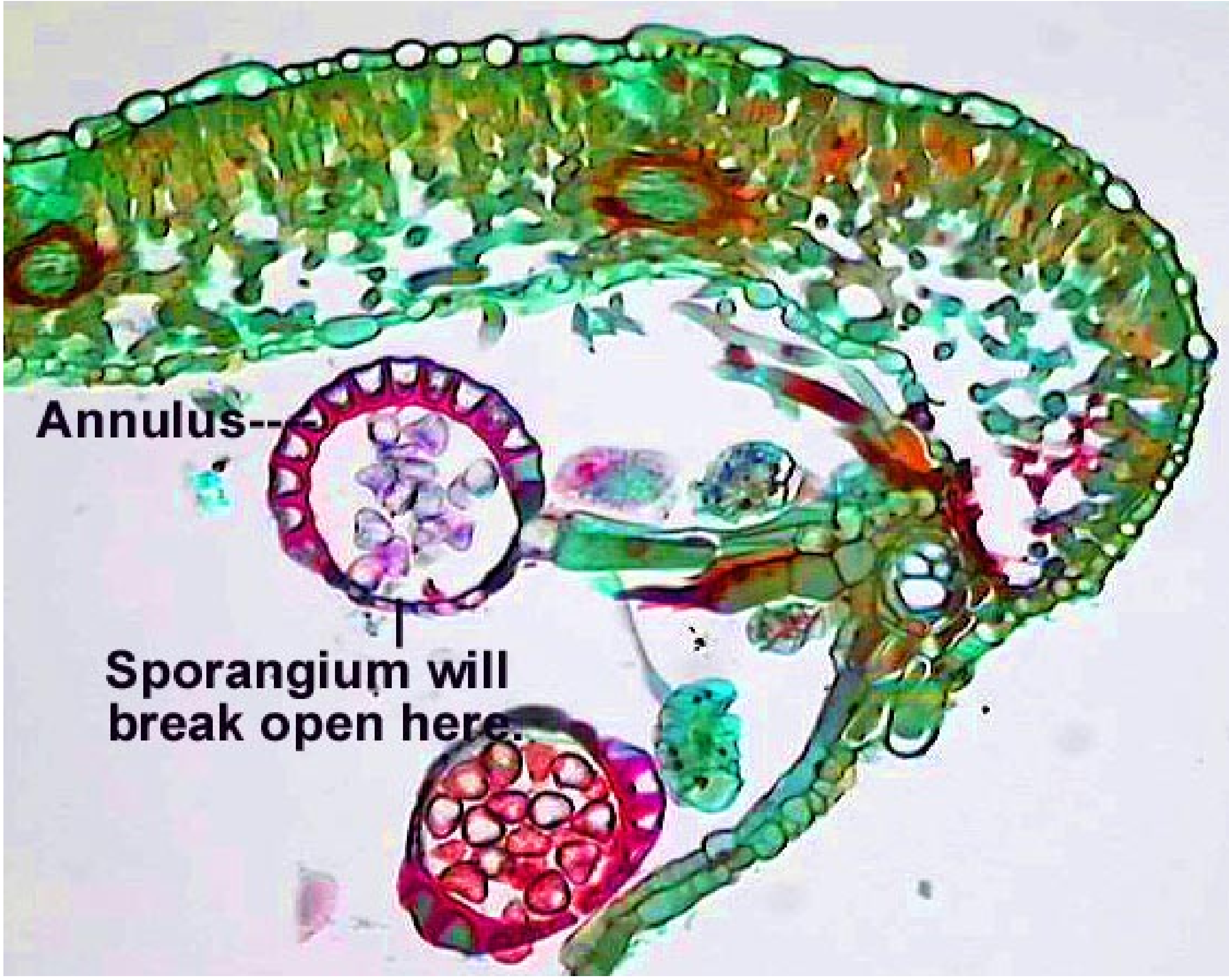
***Angiopteris* sp. (Marattiopsida)**

Synangia of *Danaea nodosa* (Marattiopsida)

Pteridopsida

- "True" ferns, about 10,000 species.
- Leaves are fronds, with apical growth. Young leaves are coiled in **fiddleheads**.
- Sporangia have one-celled wall (**leptosporangia**) and grouped in **sori** (often covered with indusium)
- Gametophyte minute, grow aboveground. Some genera of ferns are heterosporous.
- Bracken fern, *Pteridium acquilinum*, is the most widespread plant of the world.
- Many ferns have various vegetative reproduction.

Sorus, indusium, leptosporangium and annulus



Heterosporous fern *Marsilea quadrifolia*, the Shamrock. Well, almost...

Young leaves of bracken fern: Korean "gosari"

For Further Reading

References

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

Outline

48 Branching, thickening and the origin of seed

48.1 Branching

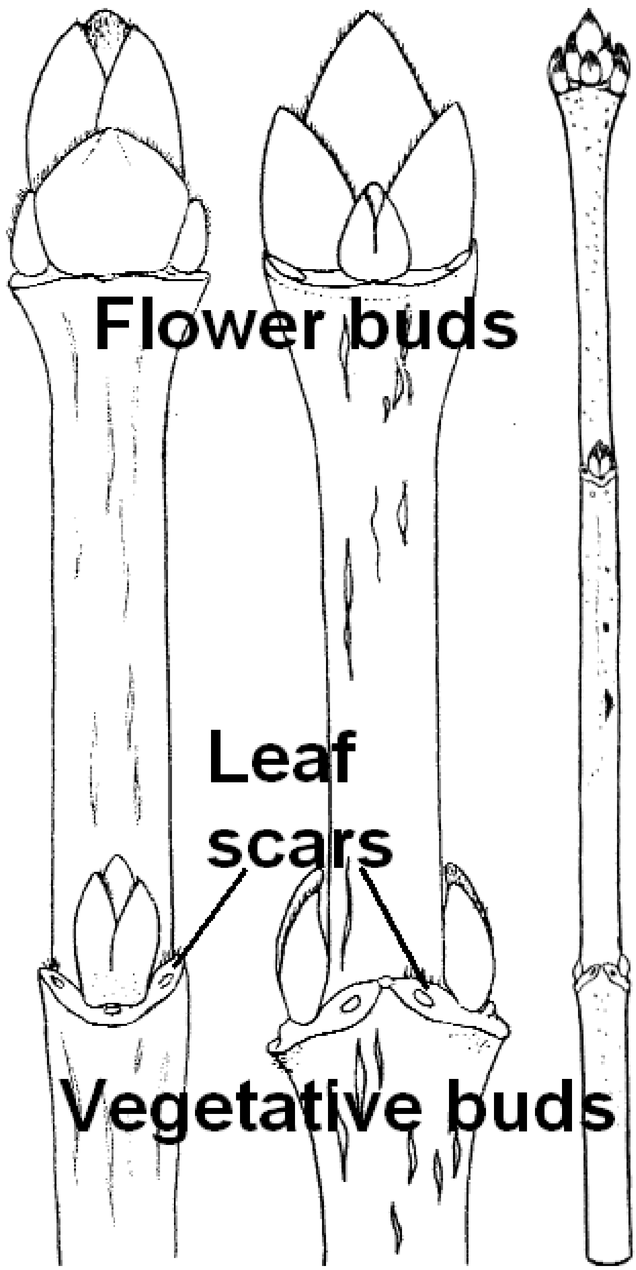
Where to see branching: winter shoot

A. Vegetative, flower, and mixed buds

B. Leaf and bud scars

C. Leaf traces

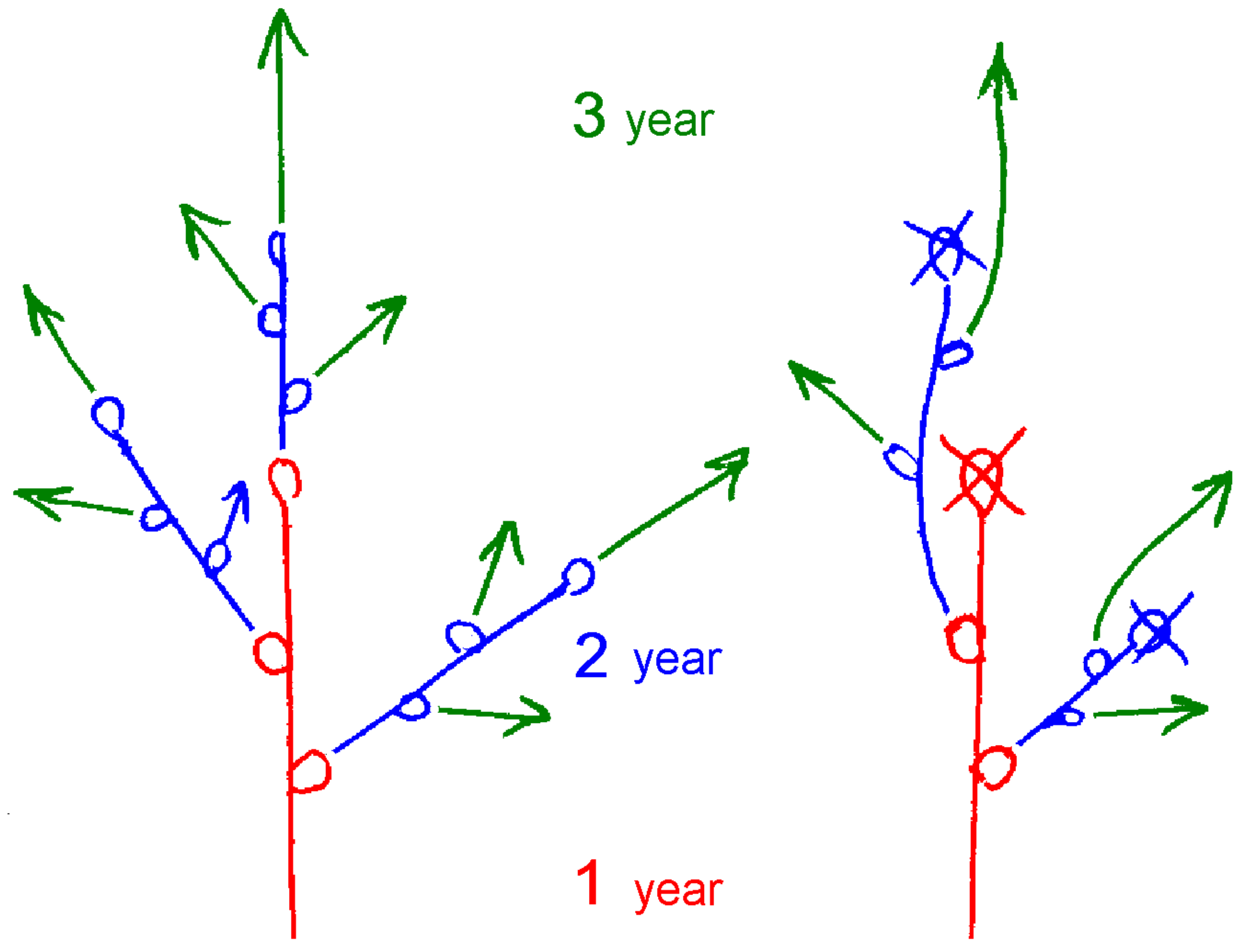
Winter shoot of maple (*Acer platanoides*)



Types of branching

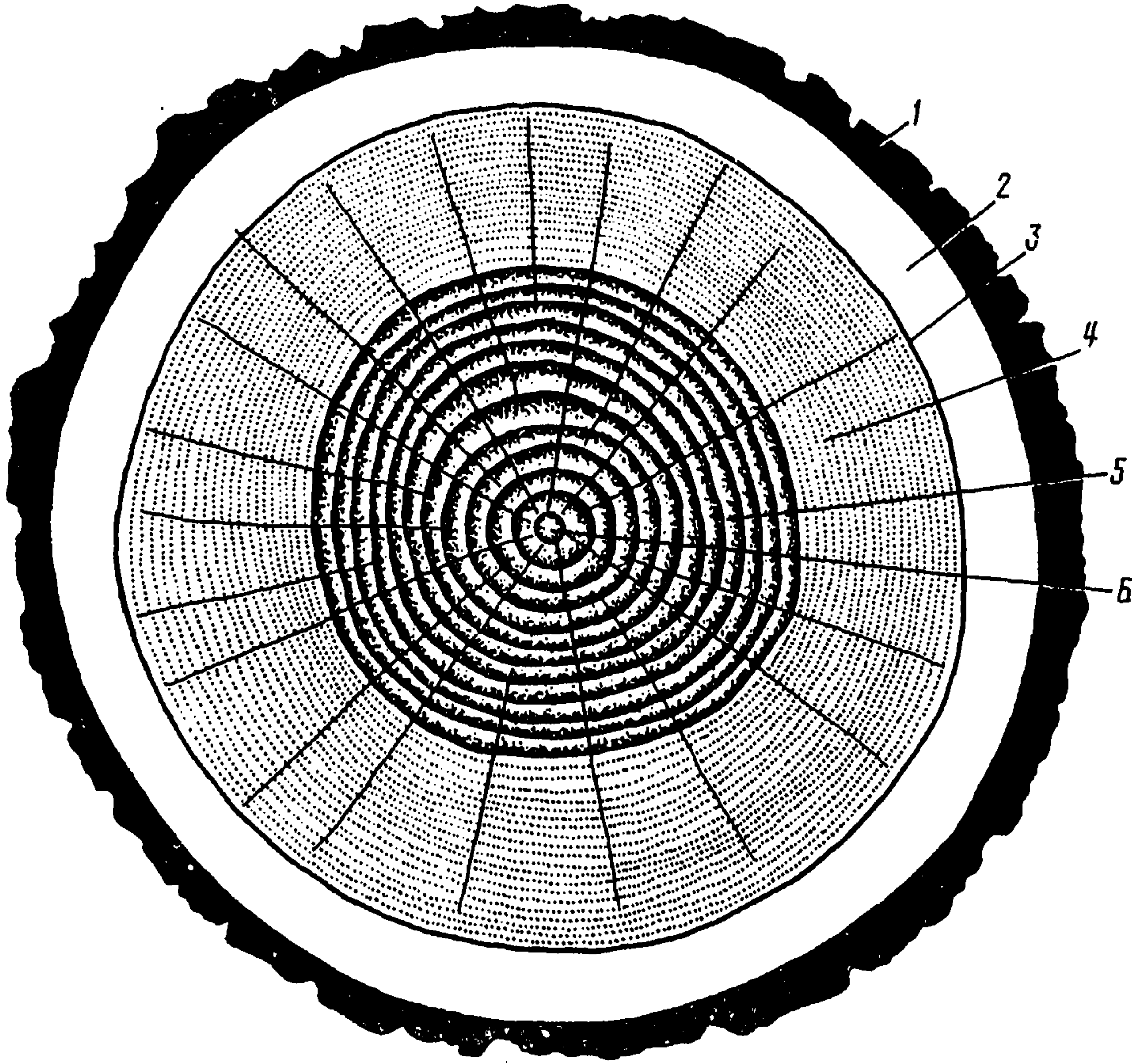
- **Monopodial**: buds do not degrade, all shoots continue to grow
- **Sympodial**: terminal buds degrade, the lateral shoot closest to terminal bud becomes terminal shoot

Monopodial (left) and sympodial branching



48.2 Secondary stem

Secondary stem = bark + wood



1 cork, 2 bast, 1 + 2 = bark, 3 cambium, 4 + 5 wood, 4 **sapwood**, 5 **heartwood**, 6 pith (if any)

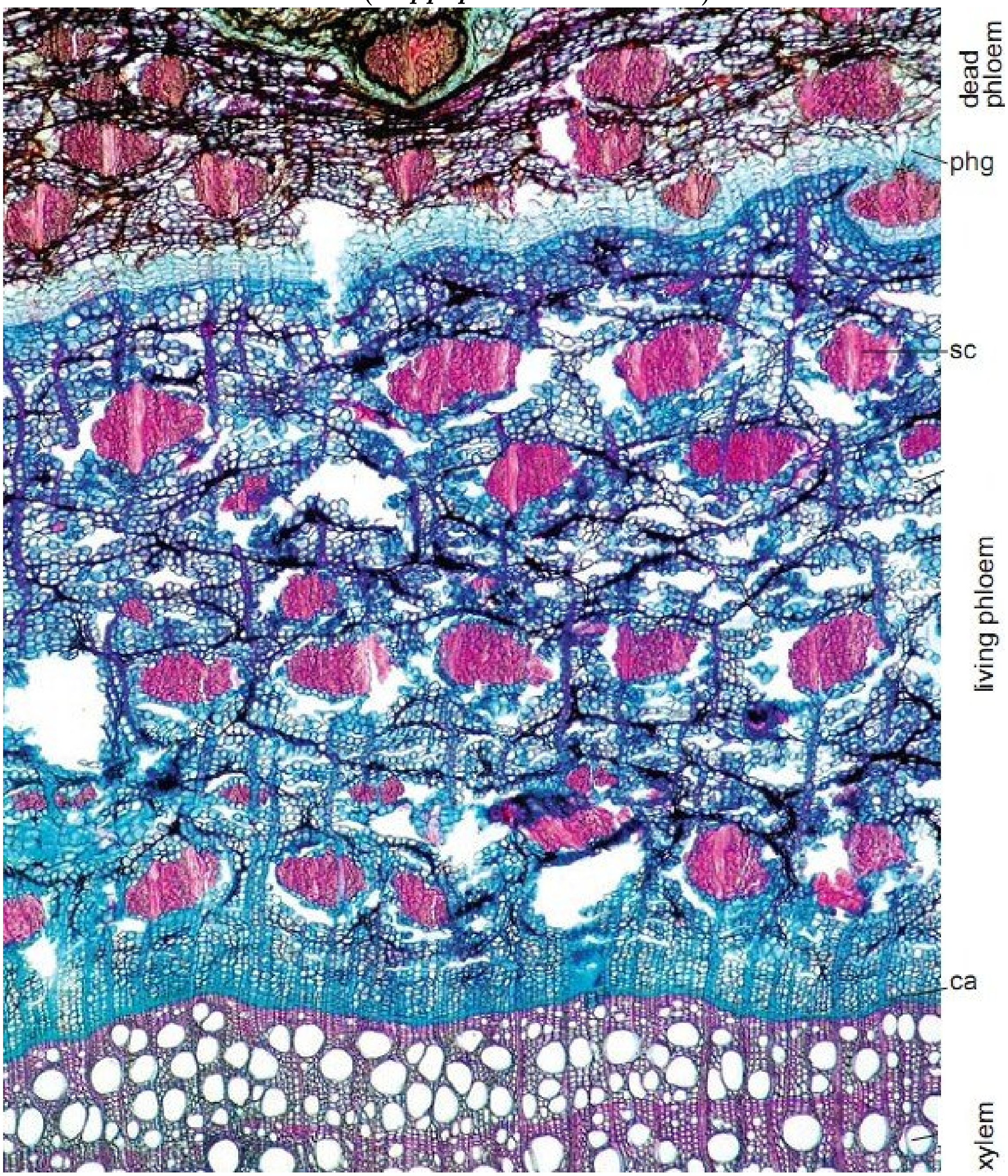
Bark, cork, periderm and wood

- **Bark** is everything outside vascular cambium, i.e. **bark** = secondary phloem + periderm [optionally, also primary phloem, cortex and epidermis]
- **Periderm** = [phelloderm] + cork cambium (phellogen) + phellem (cork)
- **Wood** = trunk − bark, or secondary xylem + [all remnants of central primary tissues]

Cork cambium and origin of bark

- Initially, cork cambium appears in cortex, works some time and then dies out
- Each year new layer of cork cambium appears from parenchyma cells of secondary phloem
- Consequently, bark consists of multiple and mostly uneven layers

Renewal of bark in sea buckthorn (*Hippophaë rhamnoides*)

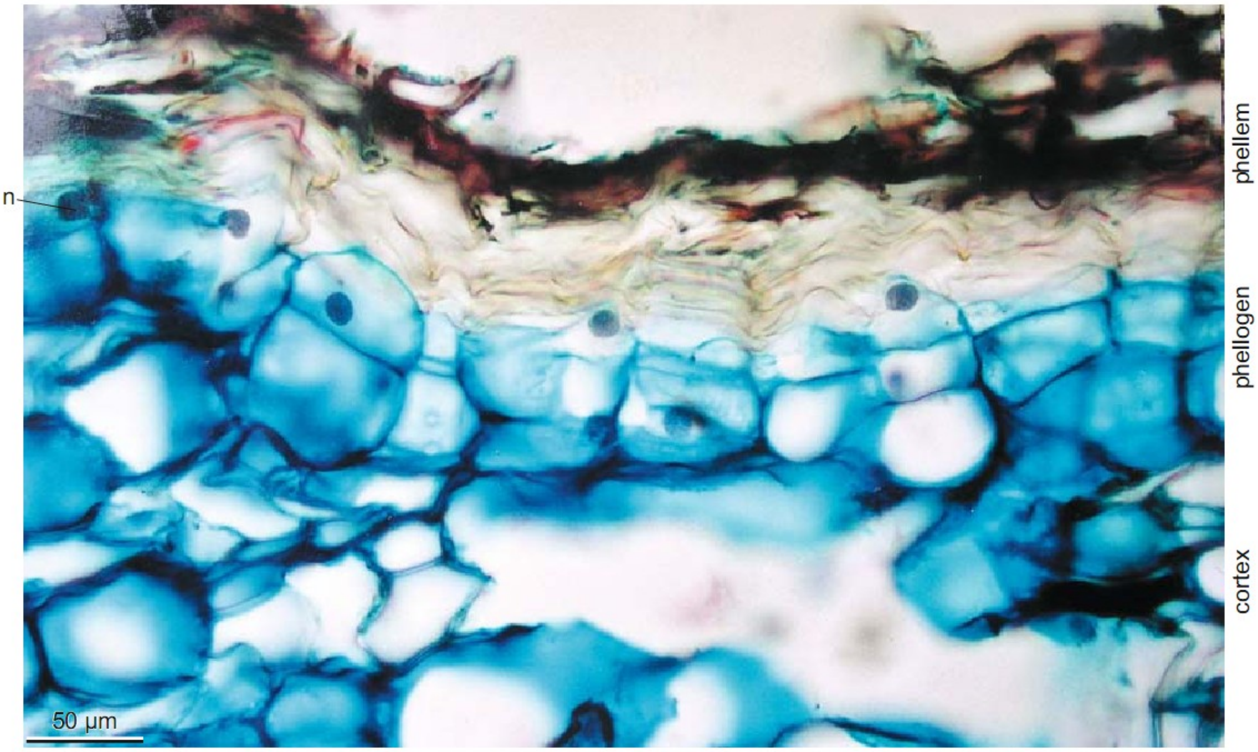


phg phellogen, ca cambium, sc sclerenchyma

Periderm

- Periderm is the product of cork cambium
- 99% of periderm is a **phellem** (cork), thick outside layer
- **Phelloderm** is a tiny layer of living cells inside of cork cambium (phellogen). Phelloderm is sometimes absent.

Formation of periderm zone in medlar (*Mespilus germanica*)

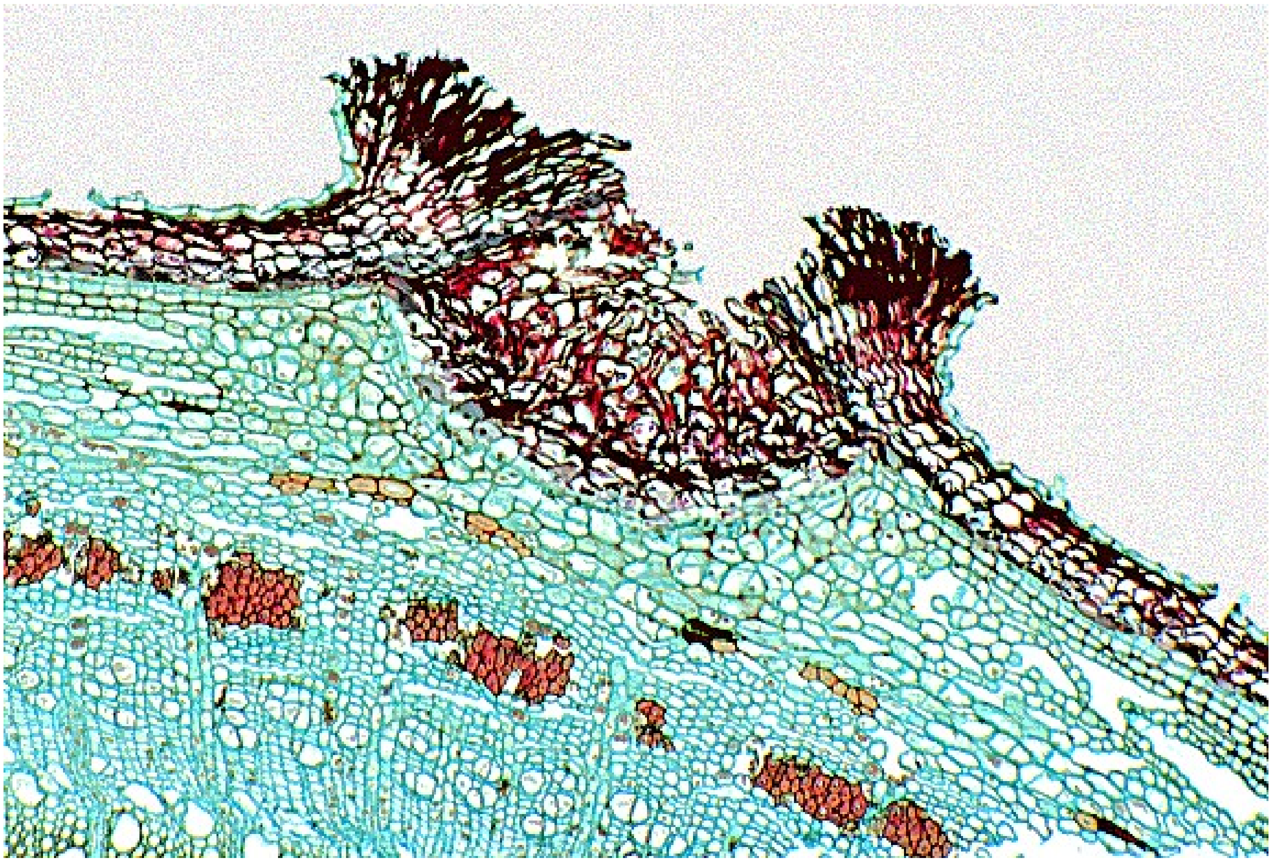


No phelloderm

Lenticels

- **Lenticels** are specialized regions of periderm; they supply stem cells with oxygen
- In order to produce lenticel, some cells of cork cambium divide and grow much faster than others

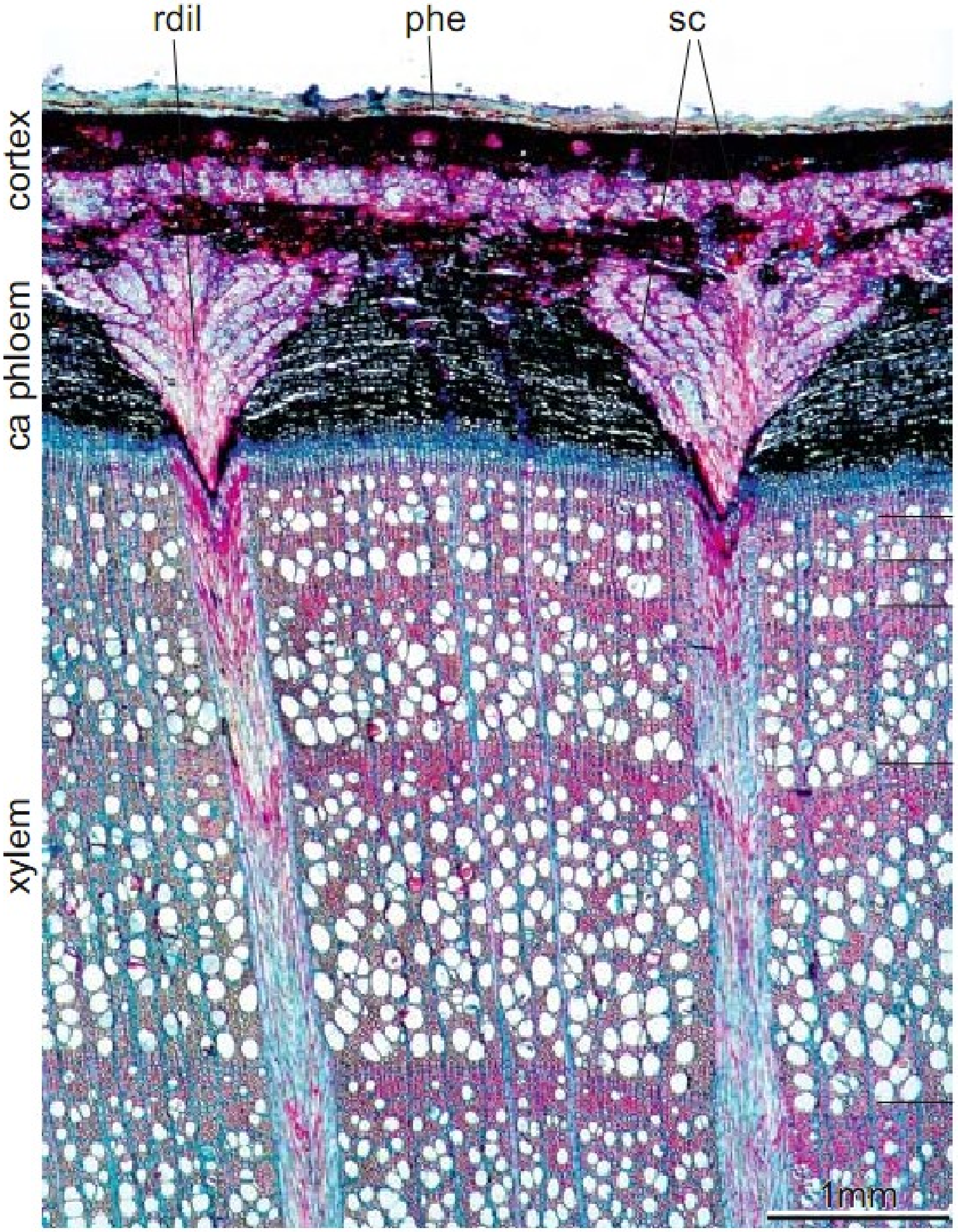
Lenticel of elderberry (*Sambucus* sp.)



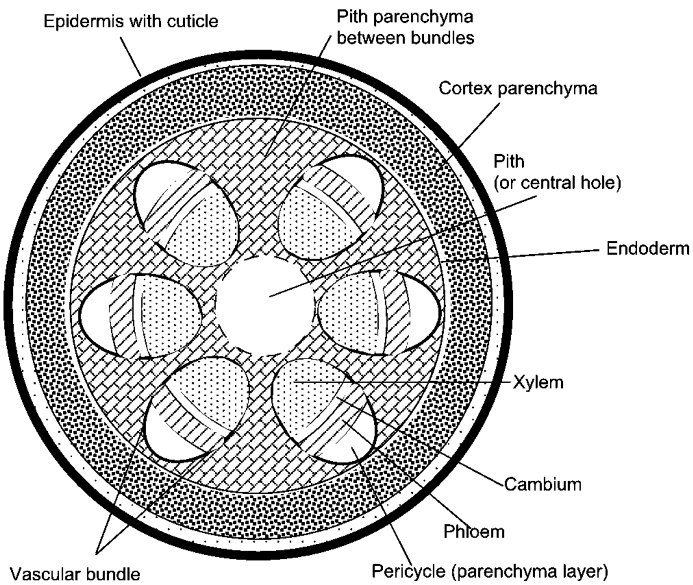
Secondary phloem (bast)

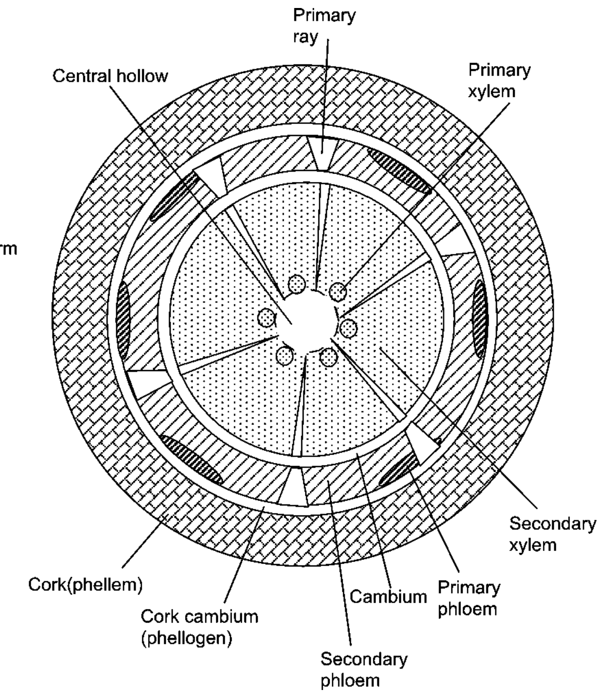
- Forms outside vascular cambium
- Rich of fibers
- Does not form annual rings
- Has rays of parenchyma cells, sometimes wedge-shaped (**dilated**)

Dilated rays in beech (*Fagus* sp.) stem

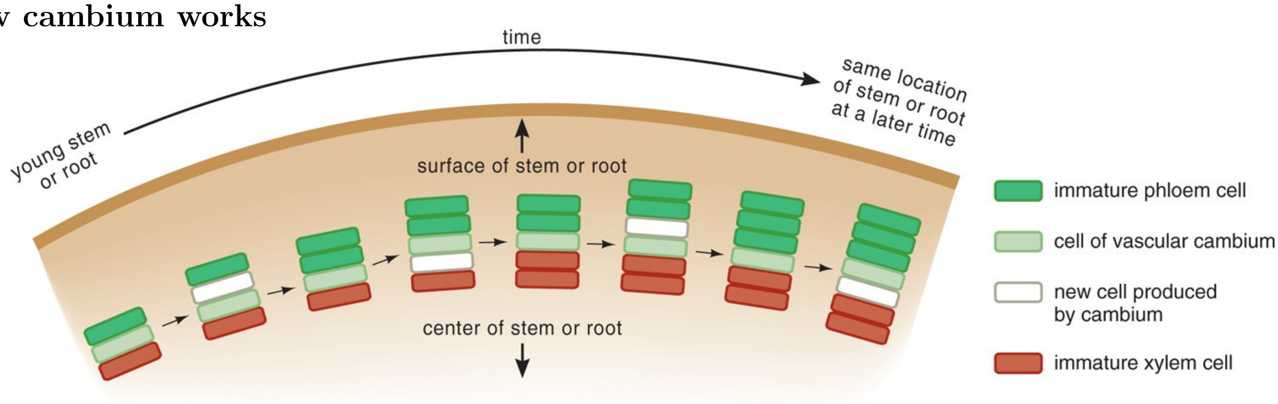


Primary and secondary stems (scheme)

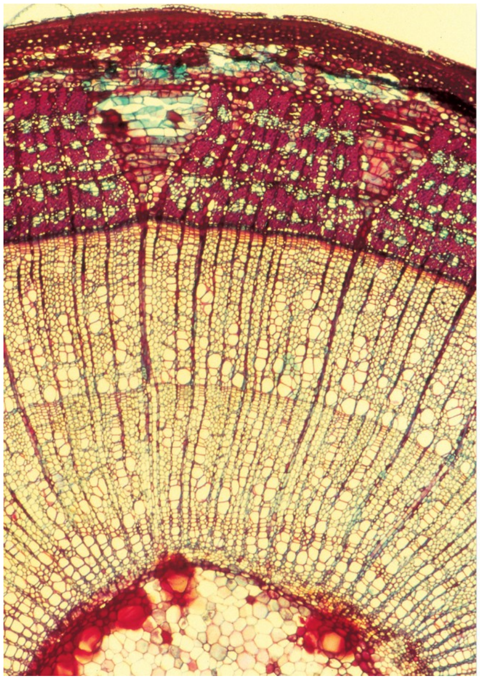


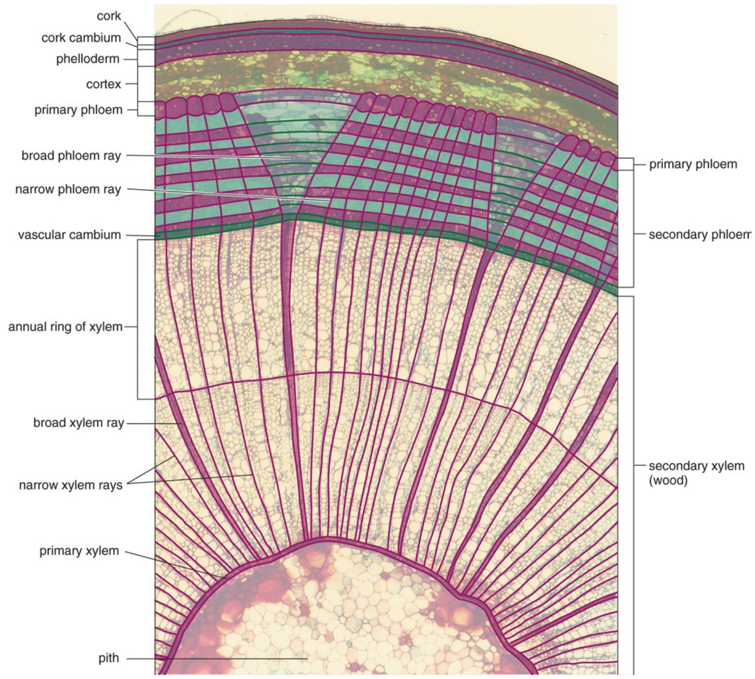


How cambium works



Secondary structure of stem (photo and explanations)

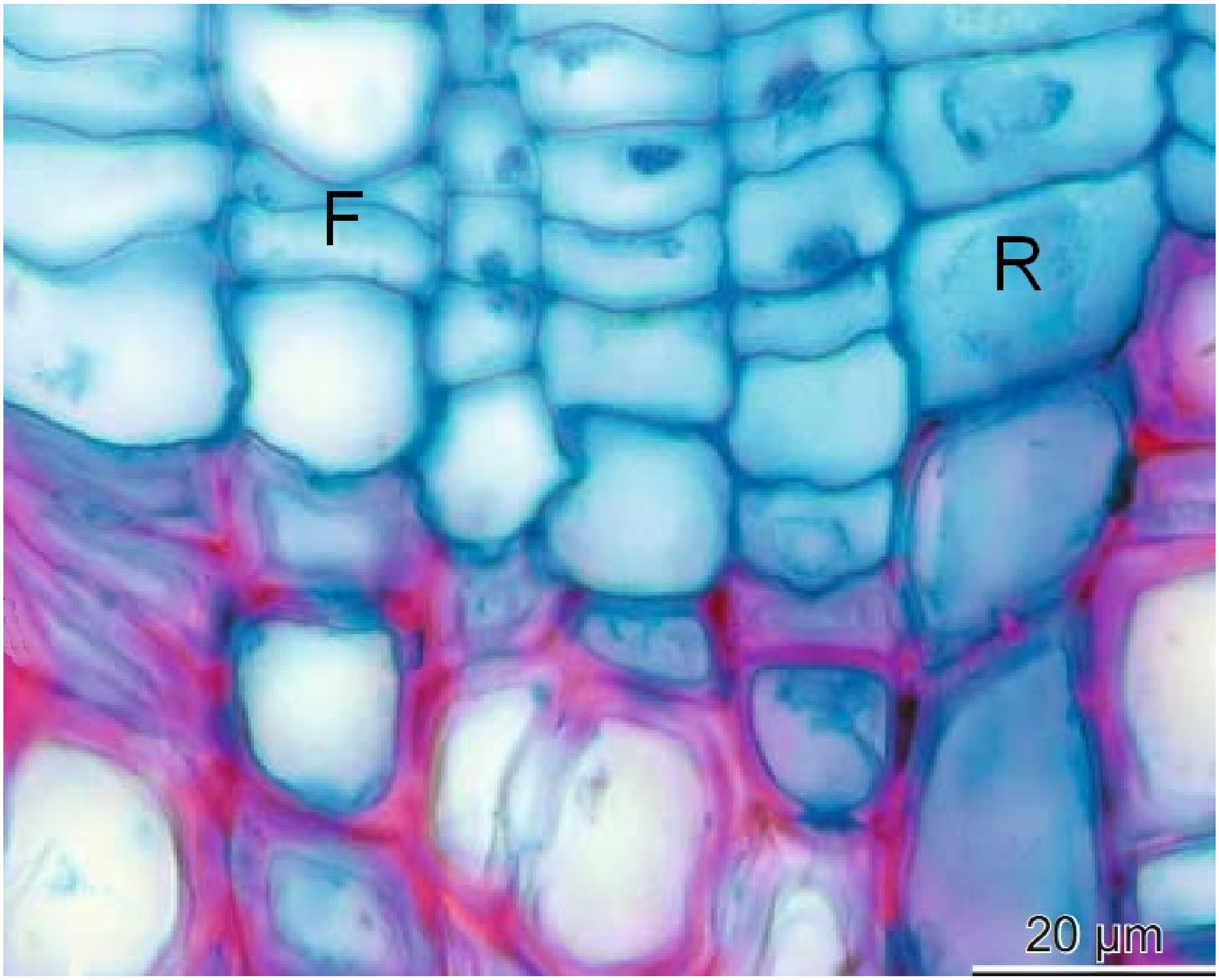




Secondary xylem and rays

- Secondary xylem, or wood, is the product of vascular cambium
- Some cambium cells are **fusiform initials**; they form axial vessel elements
- Other cambium cells are **ray initials**; they form rays (parenchyma + tracheids)
- **Rays** provide horizontal transport of water; **axial system** provide vertical transport

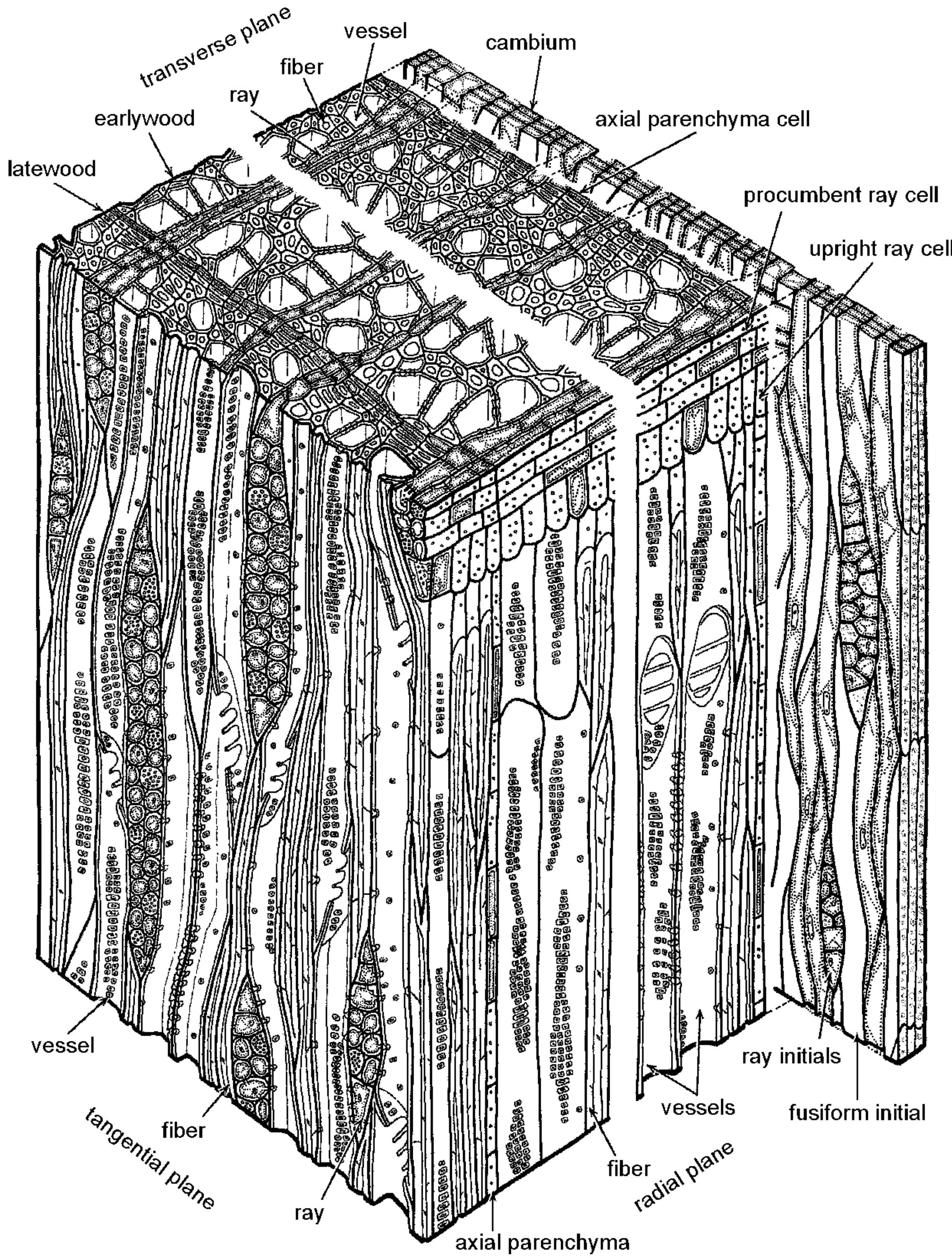
Fusiform and ray initials



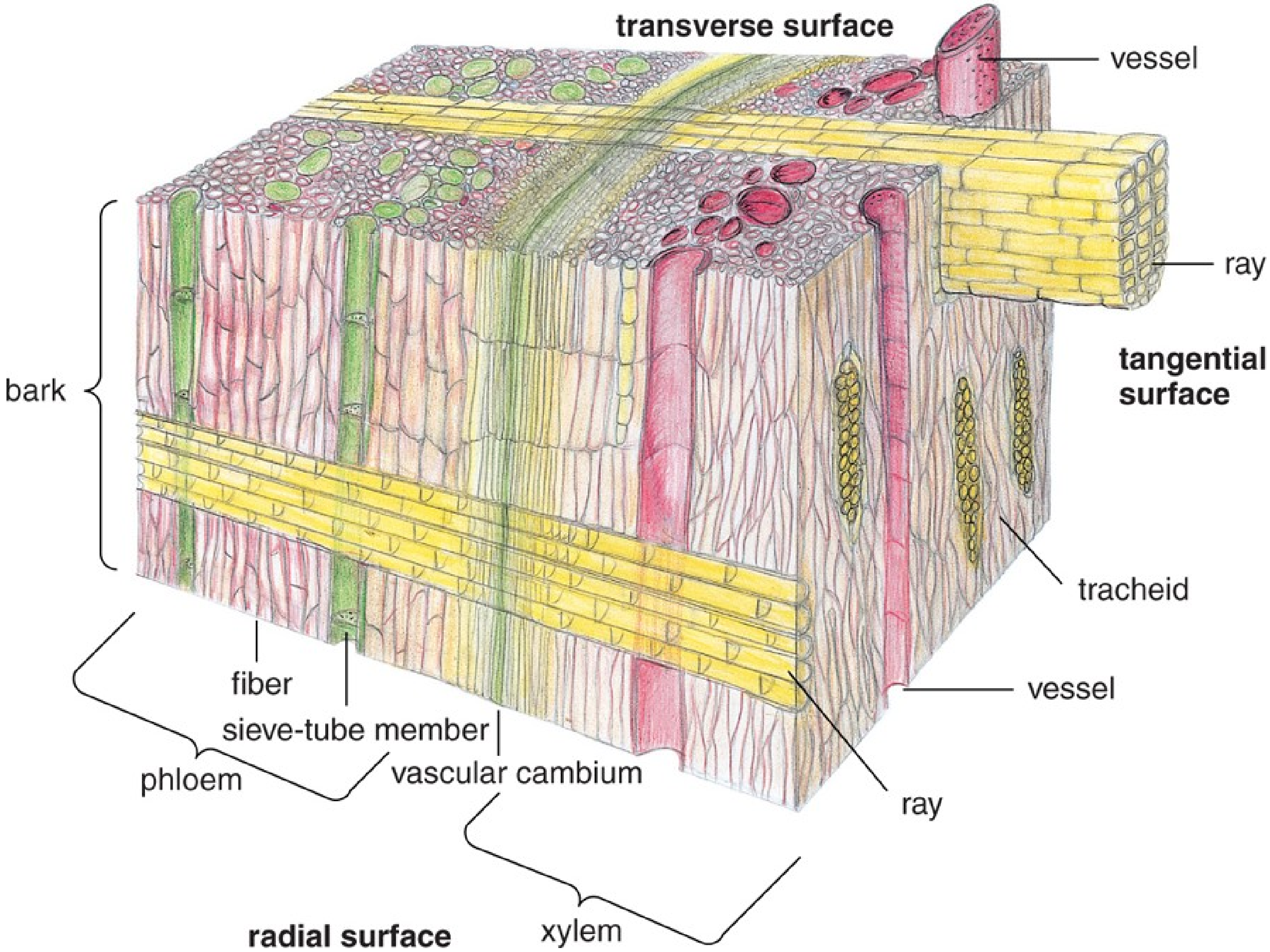
Three planes of view

- **Transverse** (cross-section)
- **Radial** (longitudinal section from center to periphery and perpendicular to stem surface)
- **Tangential** (longitudinal section parallel to stem surface)

Three plains of maple (*Acer* sp.) wood



Three plains again (the scheme)



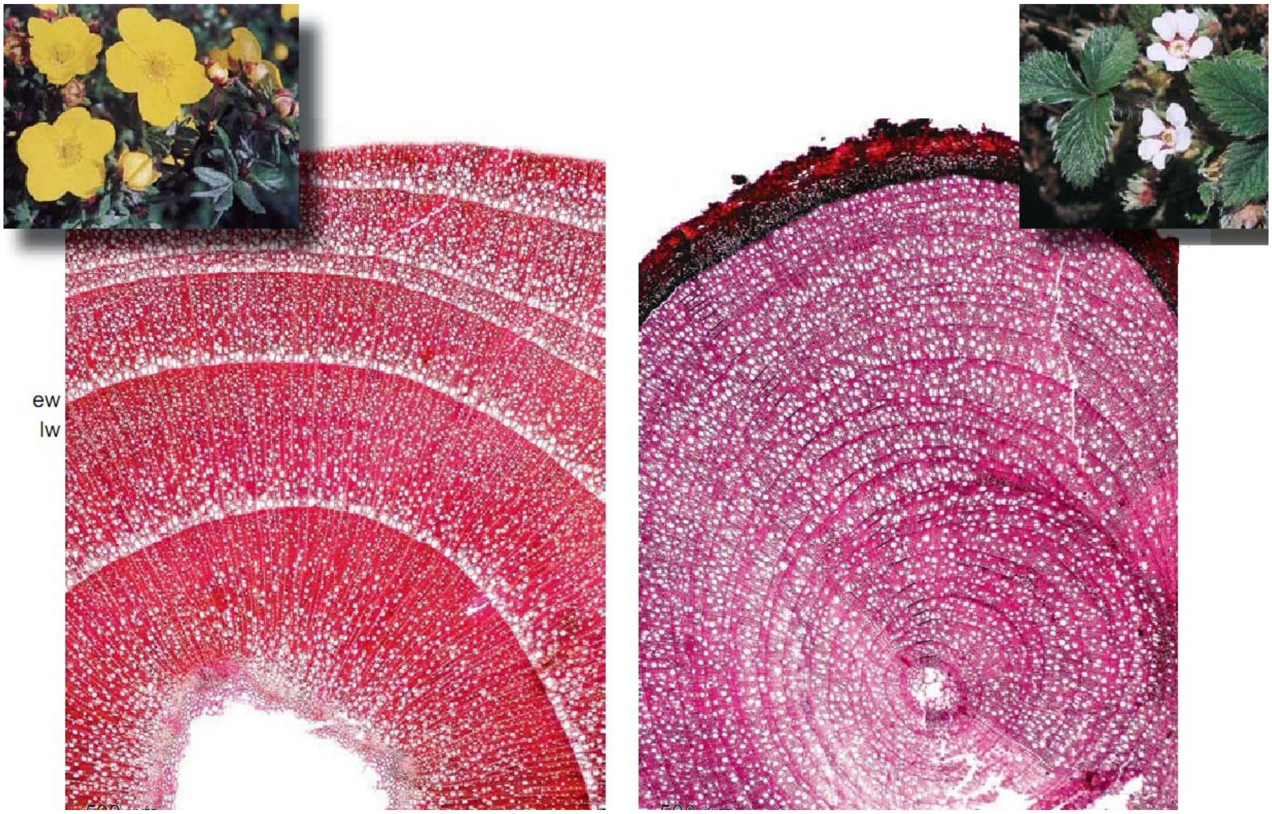
Earlywood and latewood

- **Earlywood** (springwood) contains more parenchyma and often have larger vessel elements
- **Latewood** (summerwood) often have small vessel elements and looks darker

Diffuse and ring porous wood

- In **ring porous** wood (like in red oak) bigger vessel elements concentrate in earlywood
- In **diffuse porous** wood larger vessel elements spread across early- and latewood (American elm)

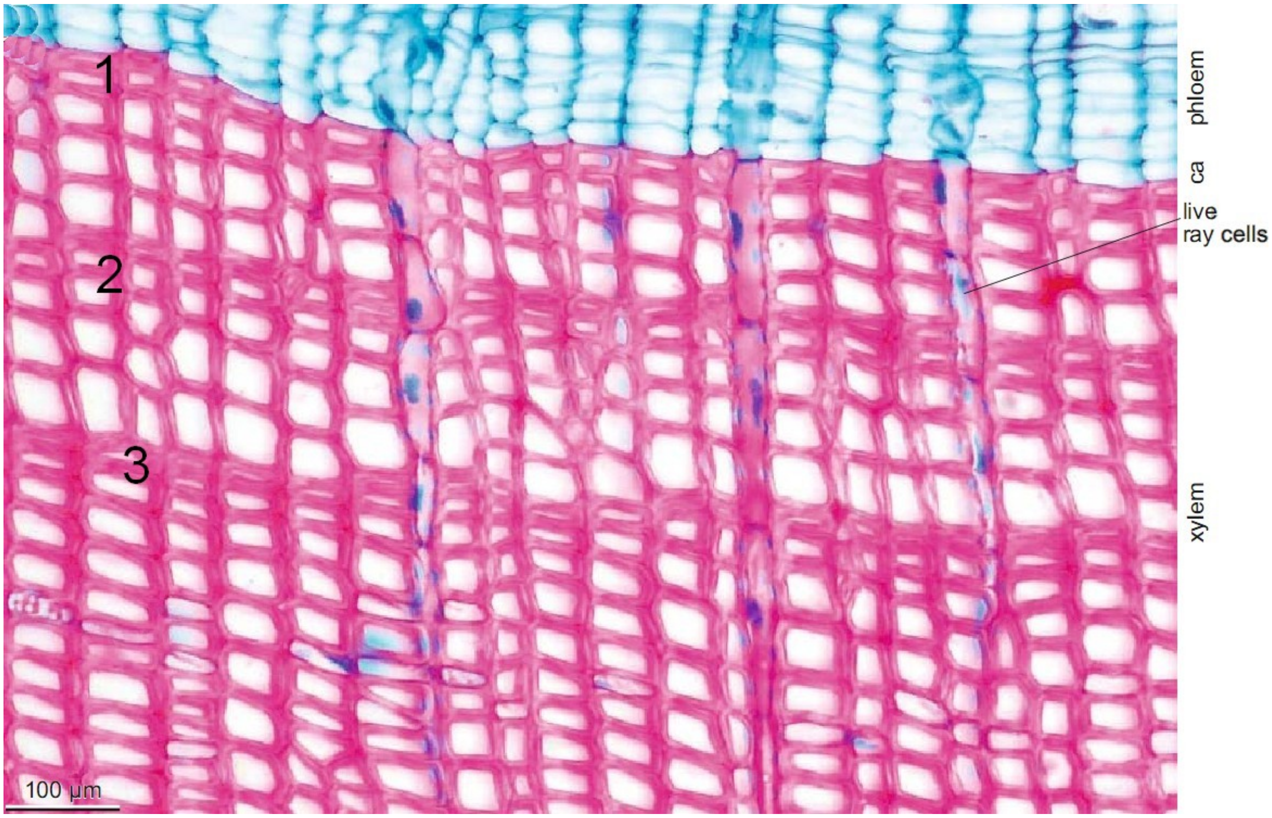
Diffuse and ring porous wood in two species of cinquefoil (*Potentilla* spp.)



Annual rings

- Interleaving early- and latewood from to sequential years form an impression of annual ring
- "Ring" is just a layer of darker (i.e., smaller) cells
- Tropical trees do not form annual rings

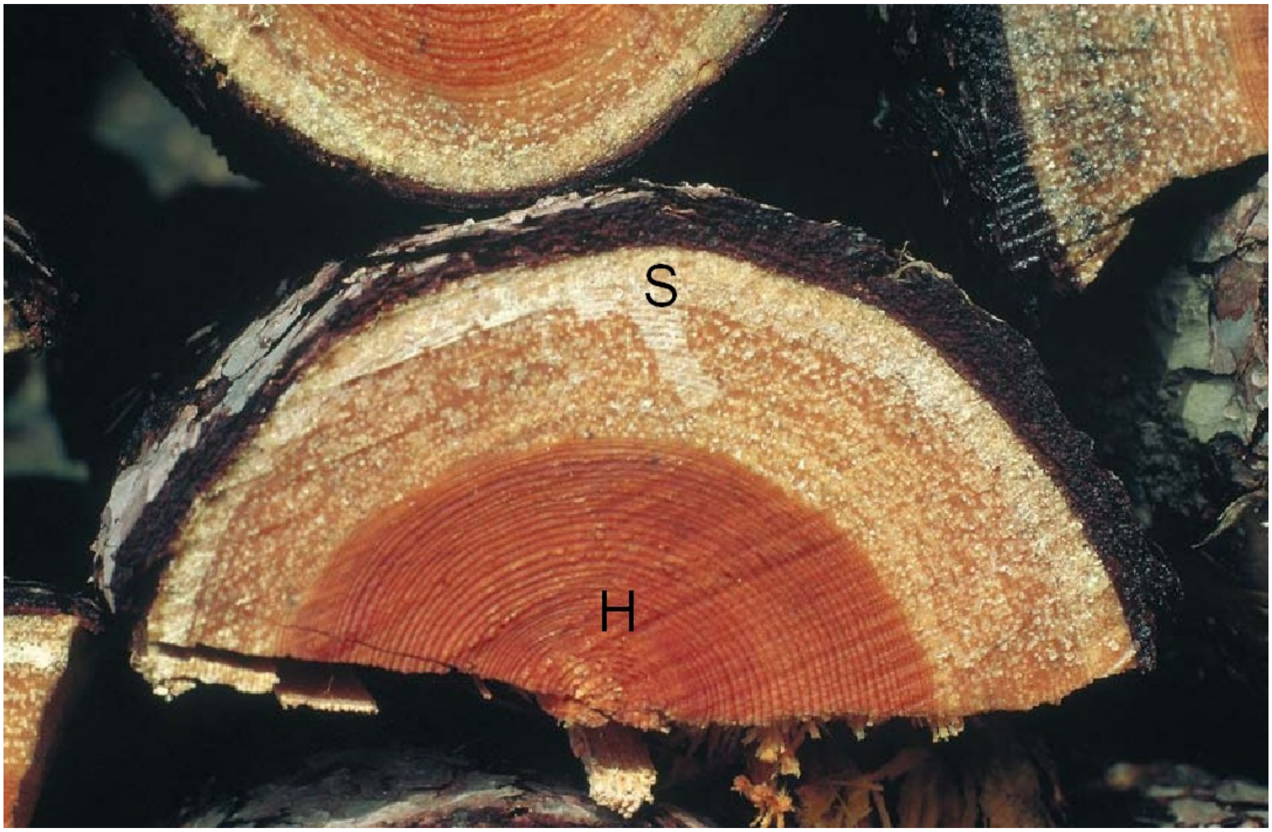
Annual rings in juniper (*Juniperus* sp.)



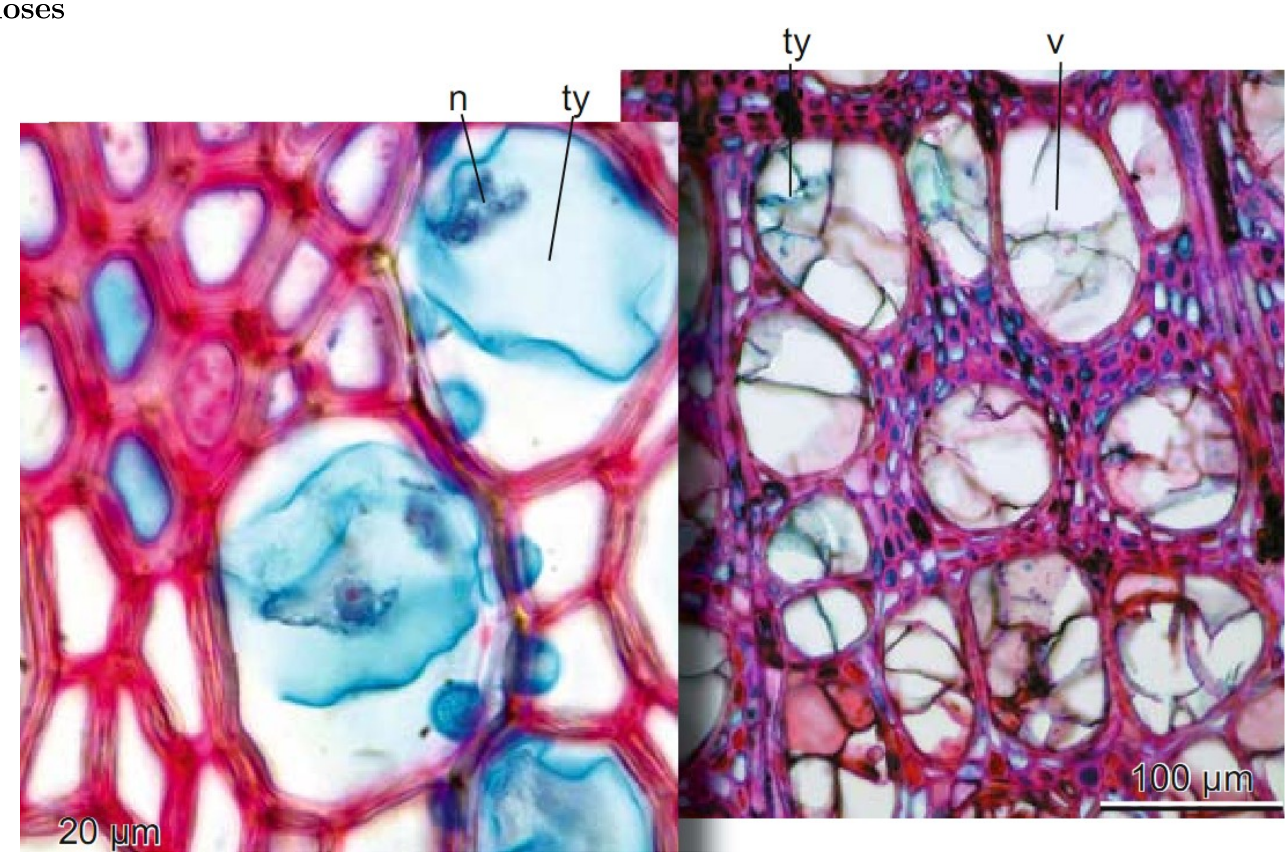
Sapwood and heartwood

- **Sapwood** is a peripheral layer of working xylem, it usually has relatively light color
- **Heartwood** is a central, non-functional, old, dark-colored xylem

Sapwood and heartwood of European pine (*Pinus sylvestris*)



Tyloses



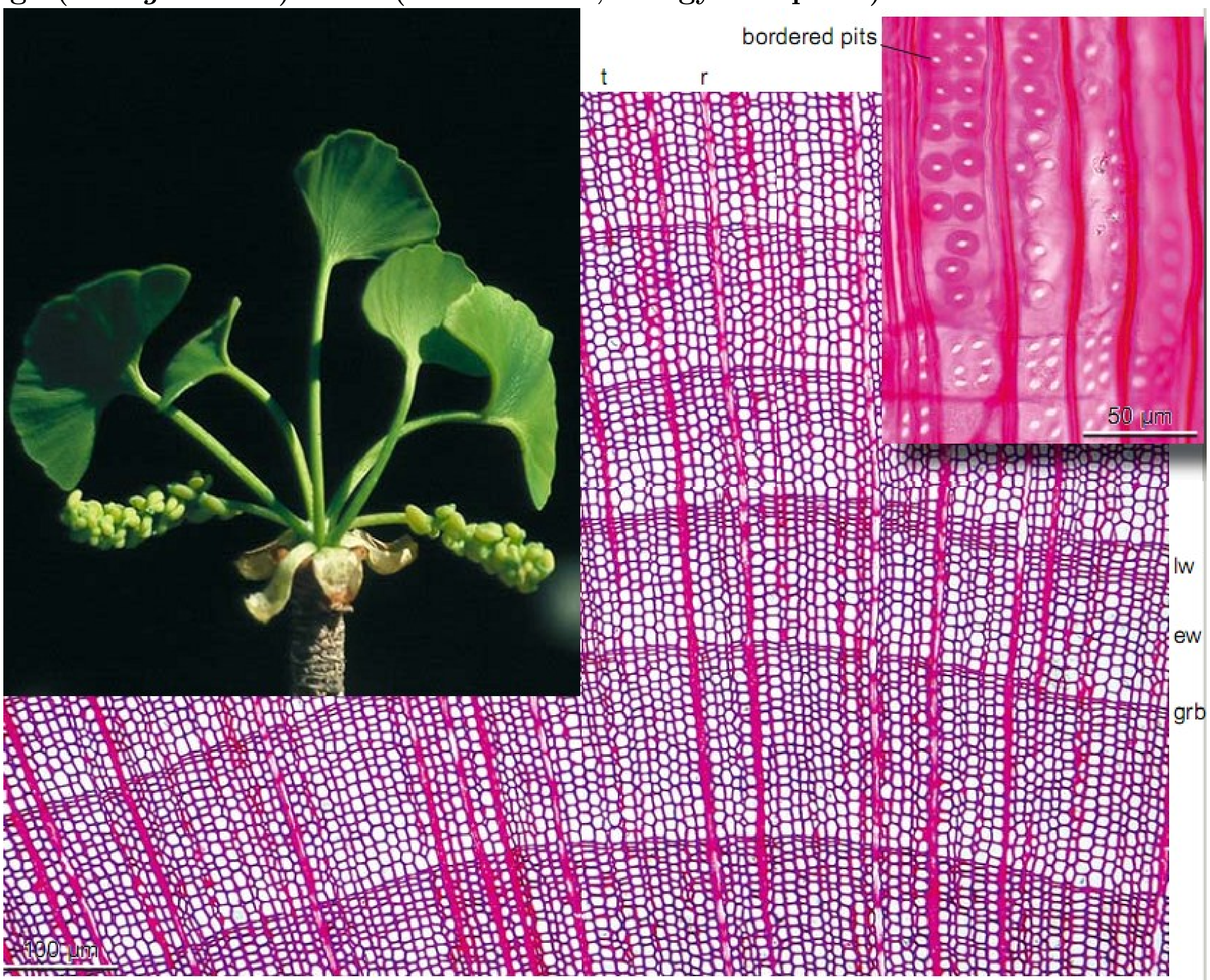
Tyloses control the winter functioning of vessels

48.3 Diversity of wood

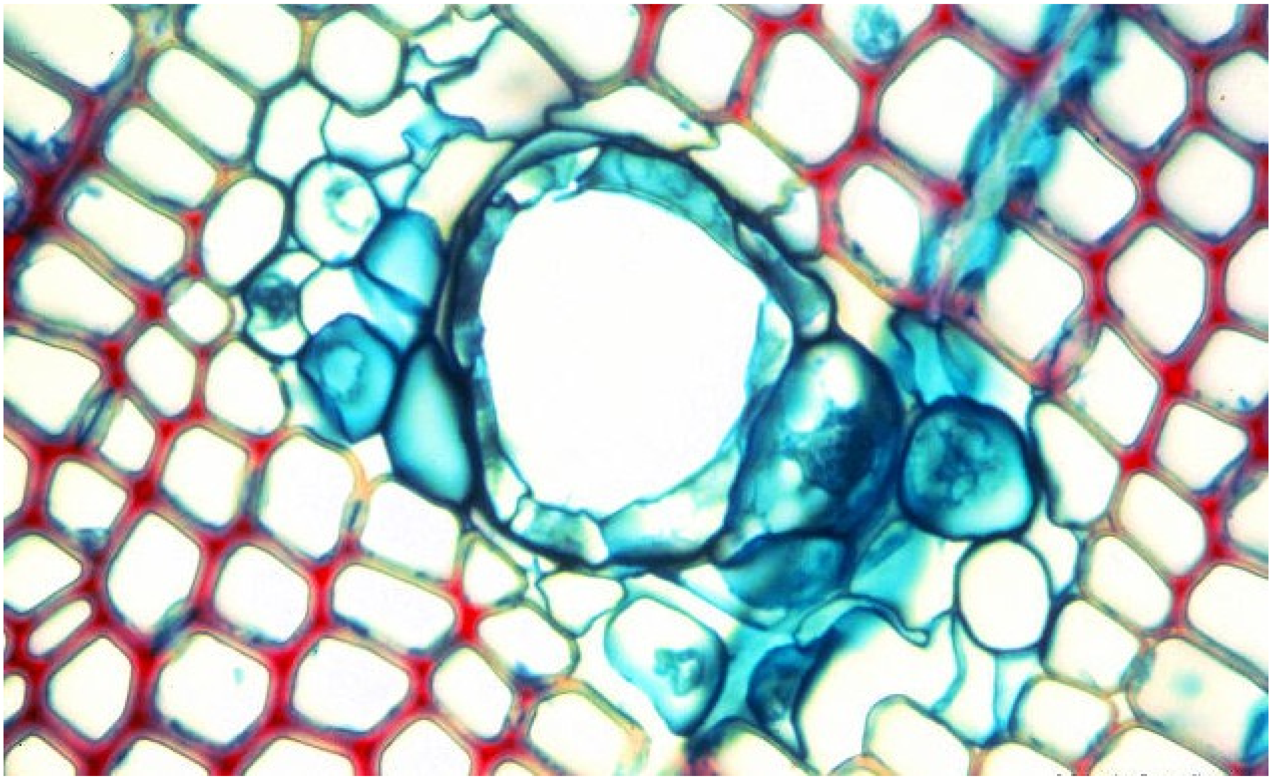
Conifer wood

- Simpler structure, few cell types
- Simple rays
- Sometimes have **resin ducts**; resin secreted by epithelial cells

Ginkgo (*Ginkgo biloba*) wood (not a conifer, but gymnosperm)



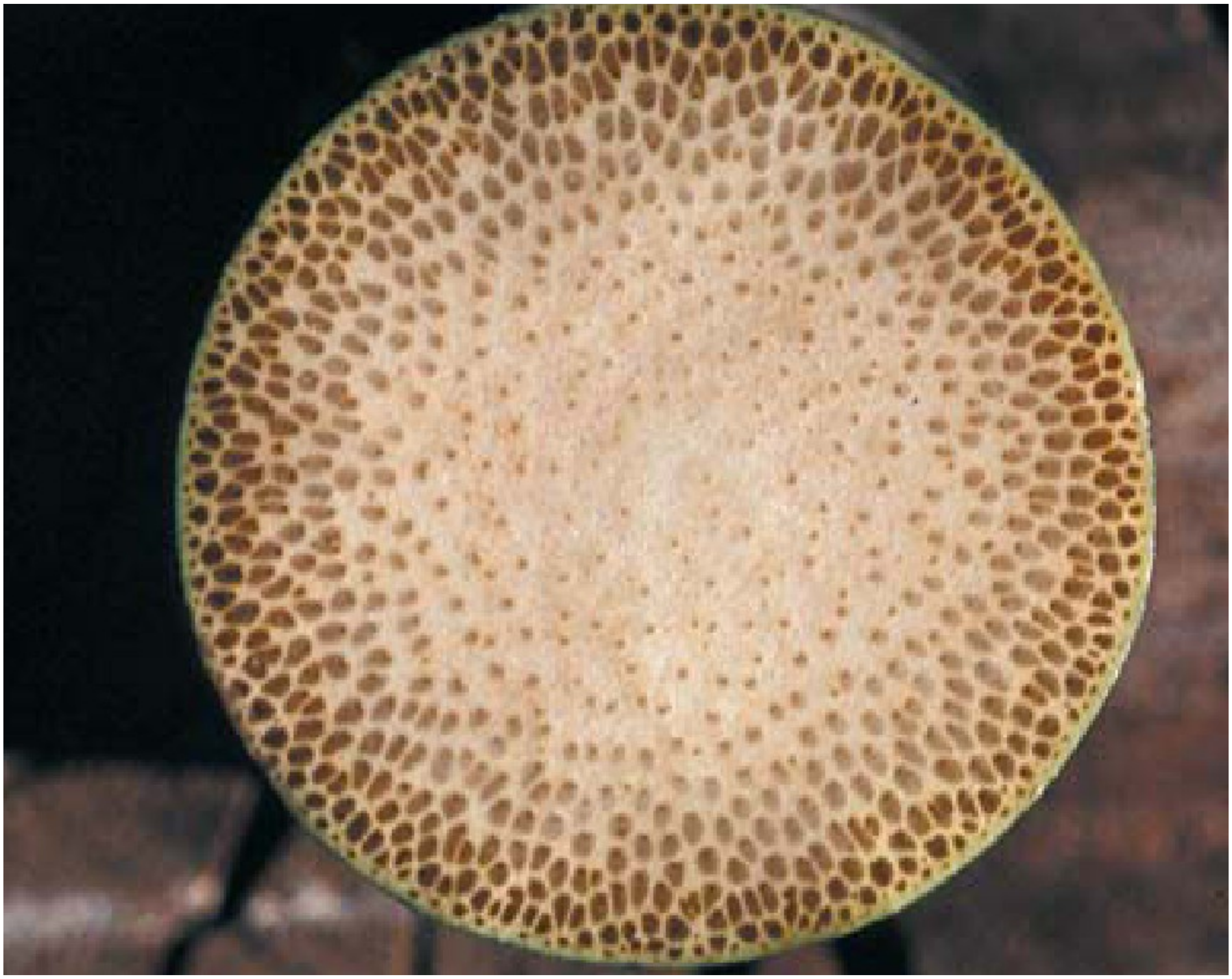
Resin duct in pine wood (©BSA)



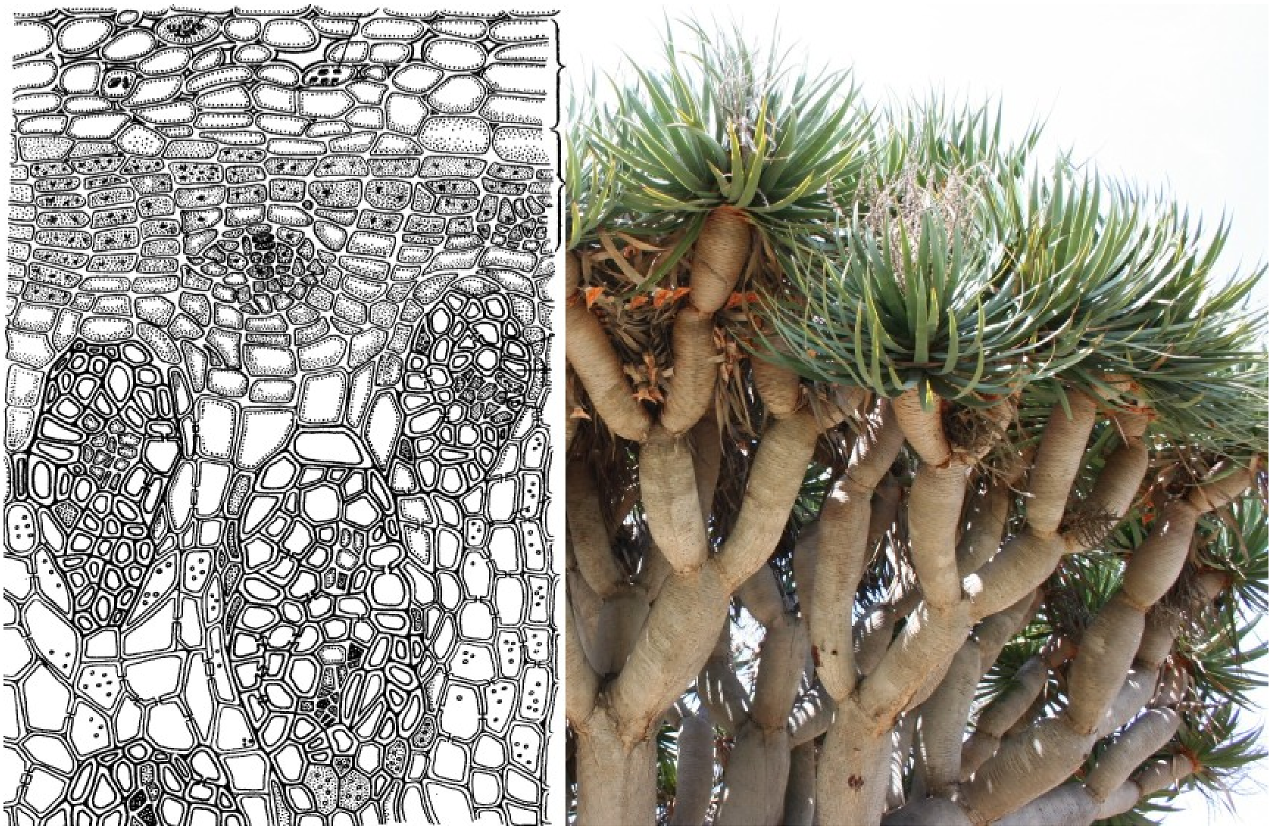
Monocot "wood"

- Most of monocots do not have lateral meristems and therefore have no true wood
- Palms have only primary tissues; their trunk widens from bottom to top
- Some monocots (dragon trees) have **anomalous secondary growth**

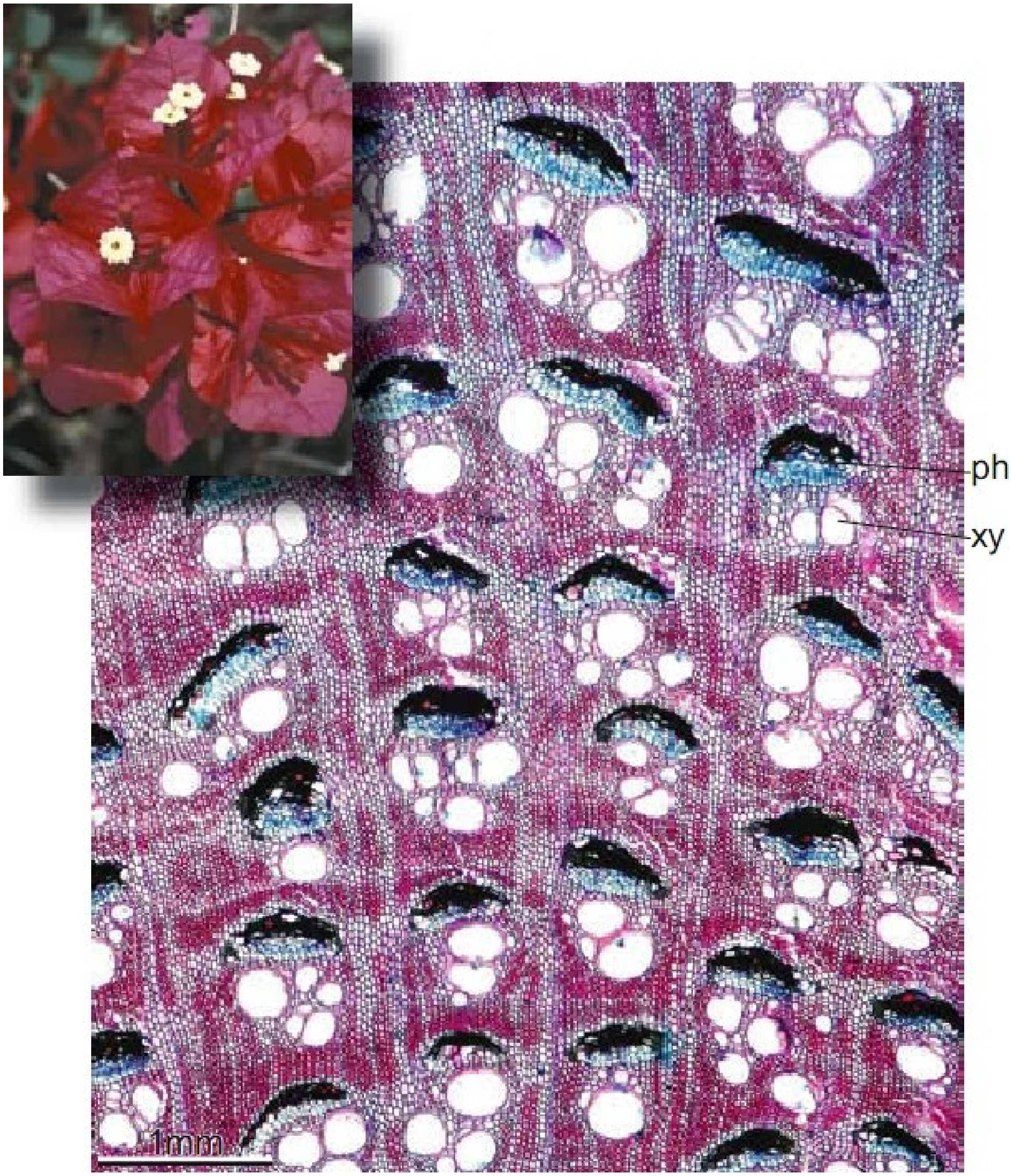
Cross section of palm (*Phoenix canariensis*) trunk



Dragon tree (*Dracaena draco*) and its anomalous cambium



Anomalous secondary growth in Bougainvillea (*Bougainvillea spectabilis*)



48.4 Life forms

Life forms

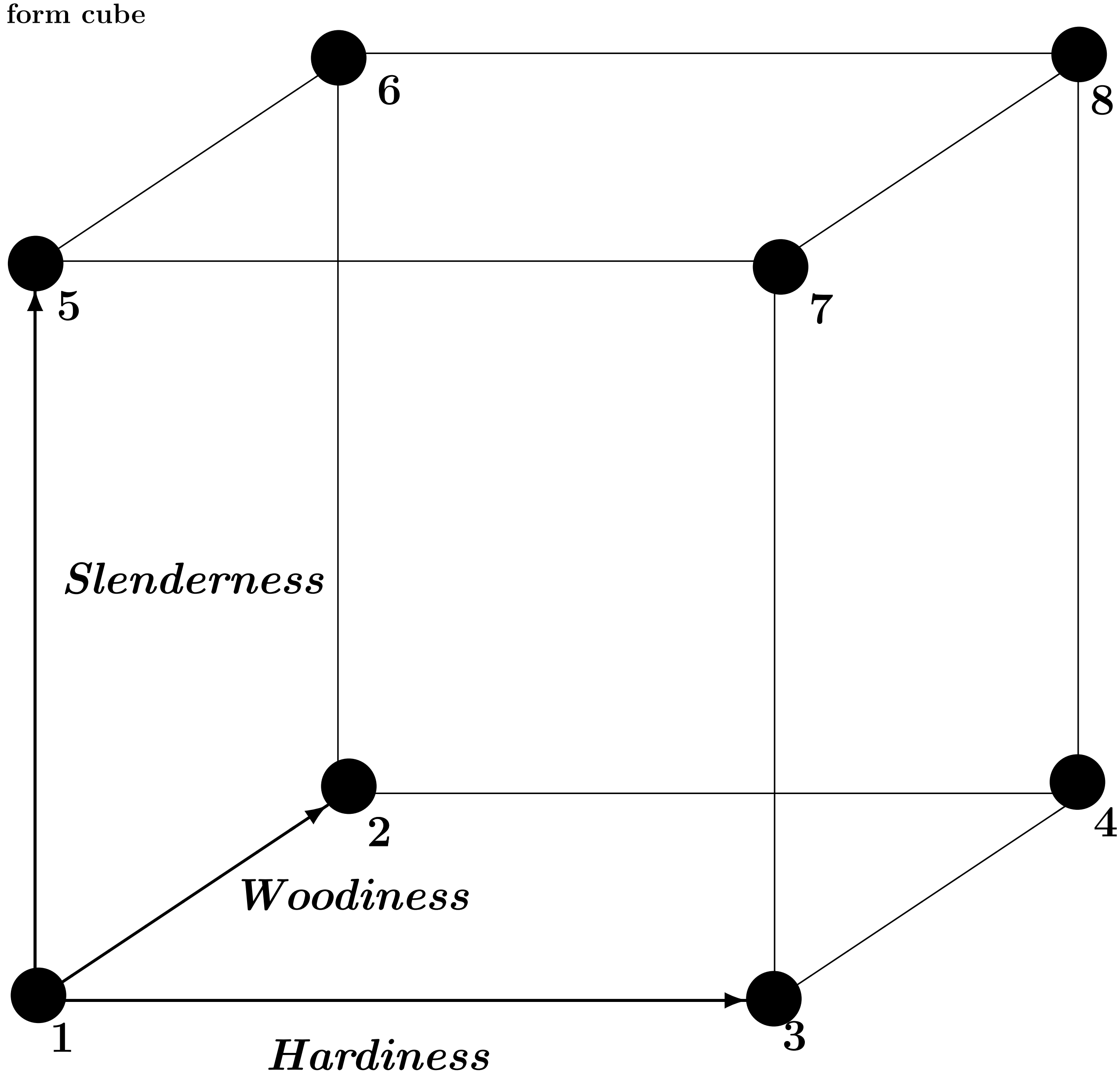
- It is a different view on the plant diversity
- Life forms represent different lifestyles
- For example, trees, shrubs, vines, annual and perennial herbs are life forms

Life forms: dynamic approach

- **Hardiness**: sensitivity to all negative influence
- **Woodiness**: % of cells with secondary walls

- **Slenderness**: proportion of linearly ordered stems

Life form cube



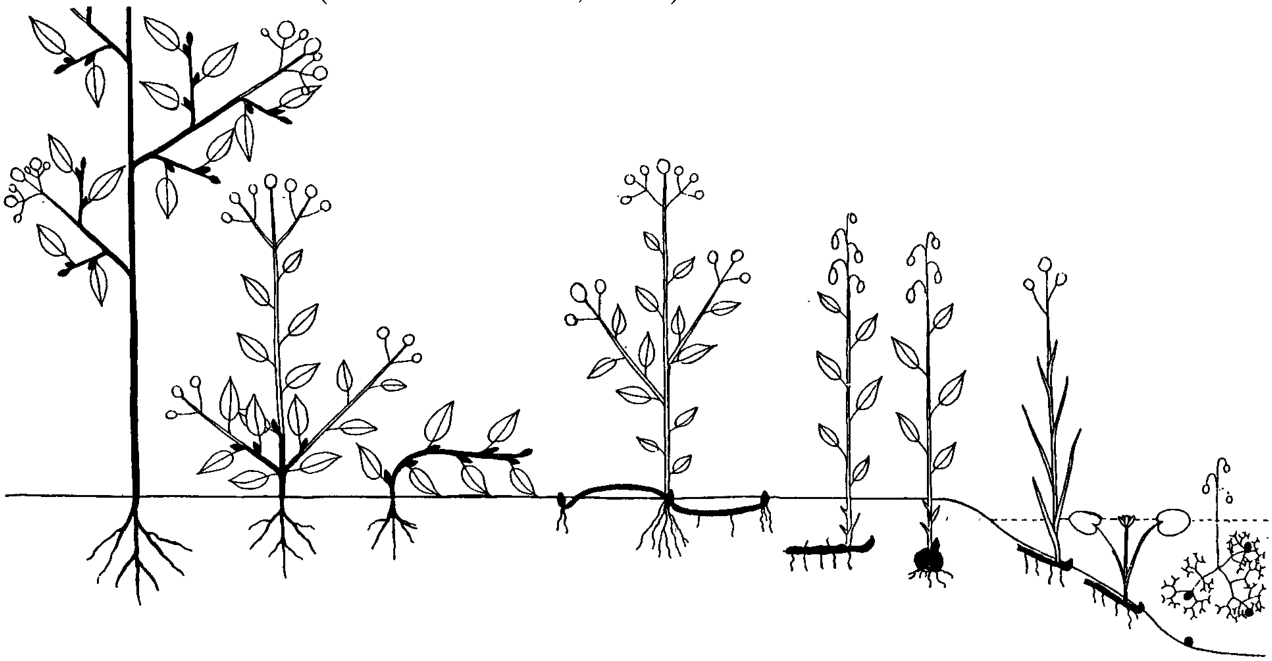
#1 could be similar to duckweed, #8—to sequoia

Life forms: Raunkiaer's approach

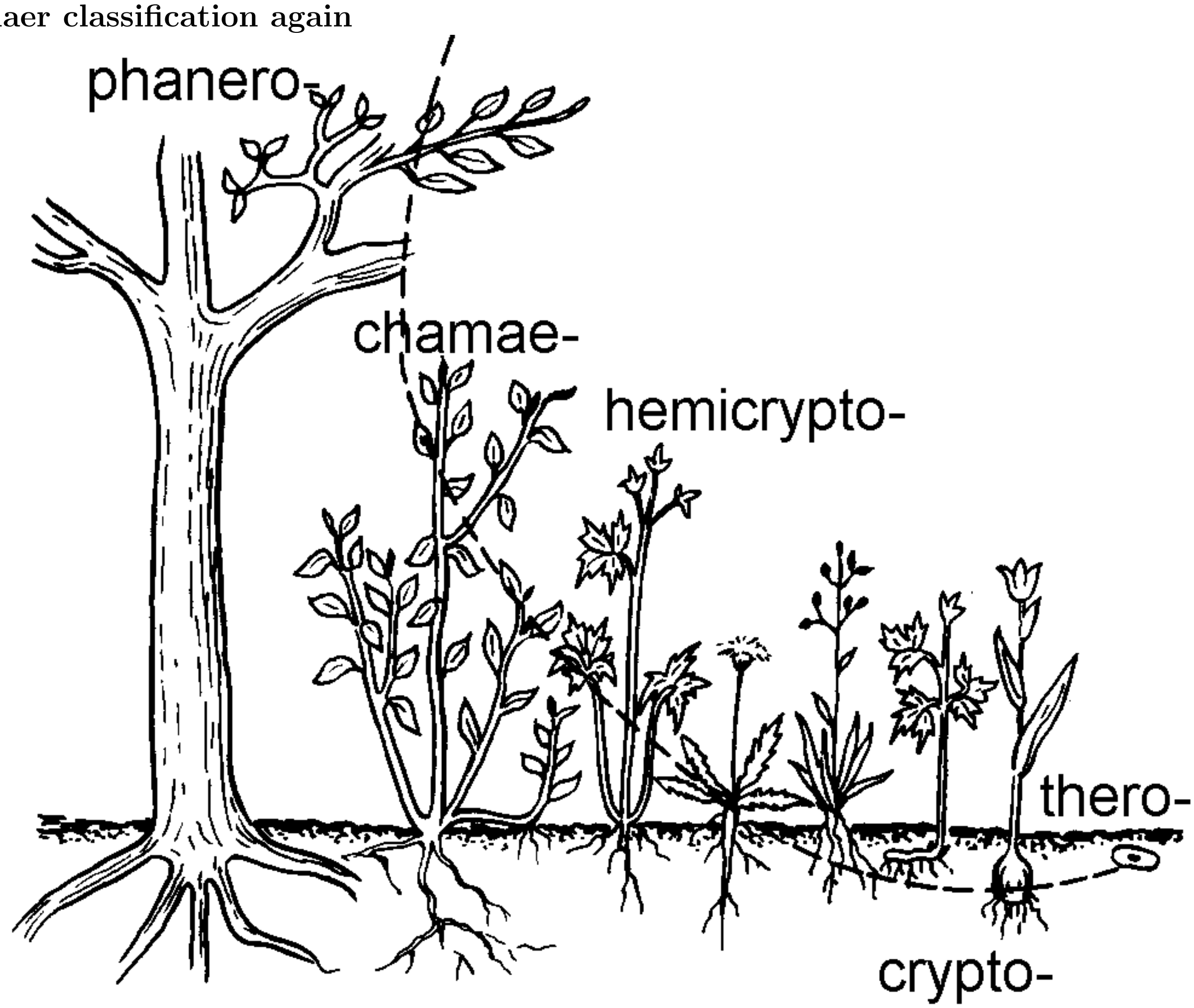
- **Epiphytes**: aboveground plants
- **Phanerophytes**: winter buds openly exposed
- **Chamaephytes**: winter buds under snow
- **Hemicryptophytes**: winter buds on soil surface
- **Cryptophytes**: winter buds in the soil
- **Therophytes**: no winter buds, only seeds

The Raunkiaer system is very useful to characterize the whole *floras*, especially temperate floras

Raunkiaer classification (after Raunkiaer, 1937)



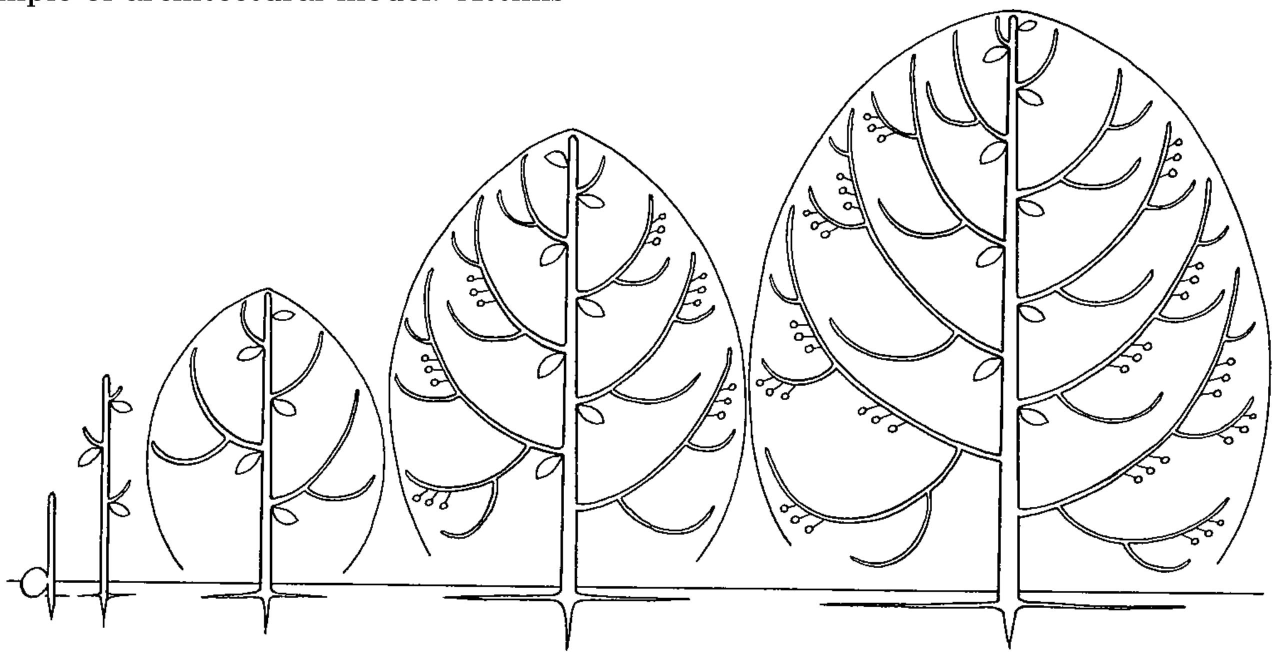
Raunkiaer classification again



Life forms: architectural models

- Developed for tropical trees, but also cover temperate forms which are less diverse
- Each model has a name of famous botanist, e.g. Thomlinson, Cook, Attims
- Based on the character of branching, development of generative shoots, directions of growing

Example of architectural model: Attims



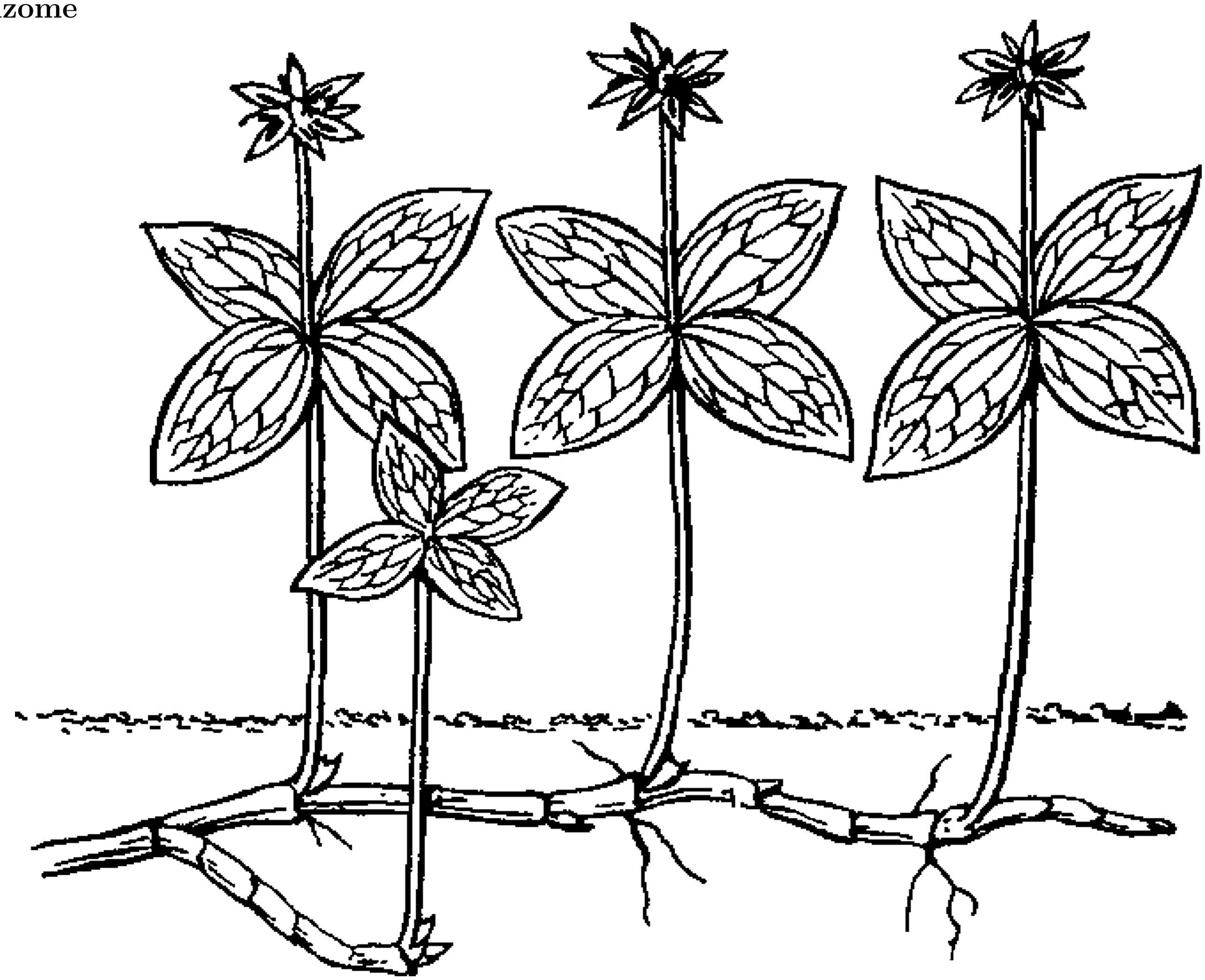
Many temperate trees are growing according to this model

48.5 Modifications of stem / shoot

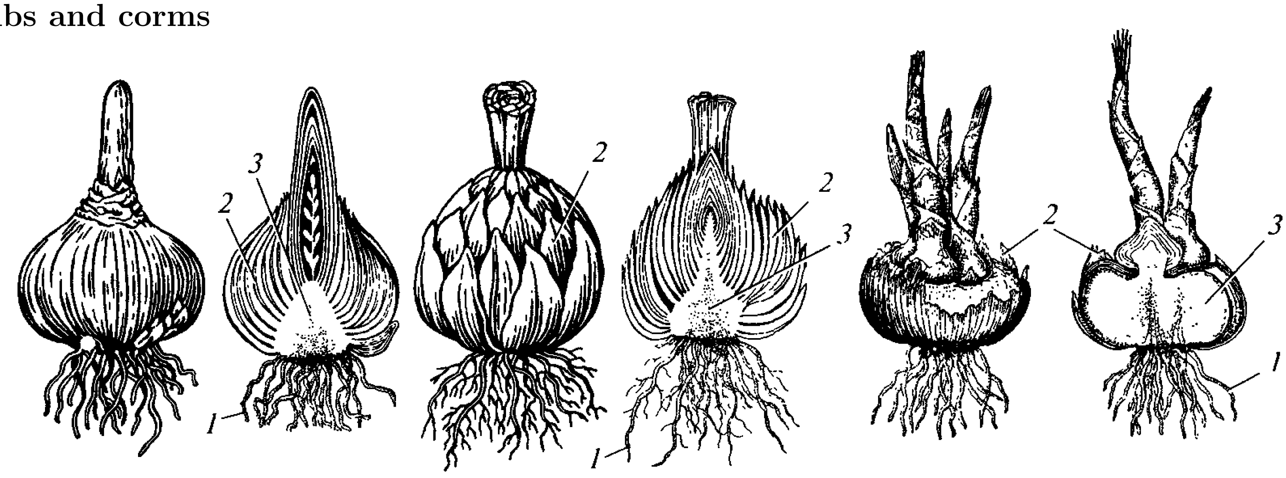
Modifications of shoots and stems

- **Rhizomes**: underground stems
- **Stolons** (runners): aboveground horizontal shoots
- **Tubers**: enlarged portions of rhizomes
- **Bulbs**: storage shoots, leaves > 50% of volume
- **Corms**: storage shoots, leaves < 50% of volume
- **Thorns**: defense shoots
- **Spines**: defensive emergencies of stem surface
- **Cladophylls**: leaf-like shoots
- **Stem traps**: catch animals for some carnivorous plants

Rhizome

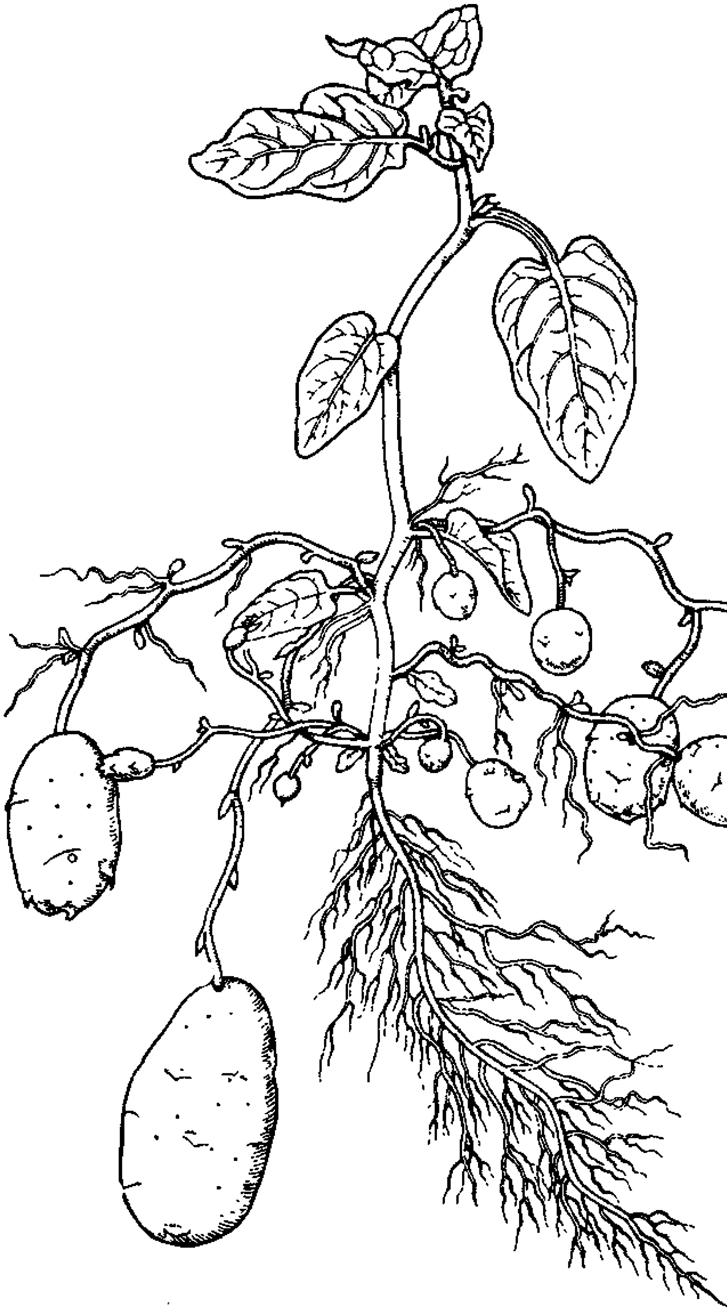


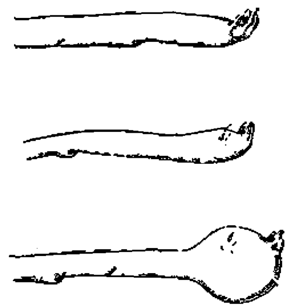
Bulbs and corms



(1) roots, (2) leaves, (3) stems

Tubers: potato and orchids

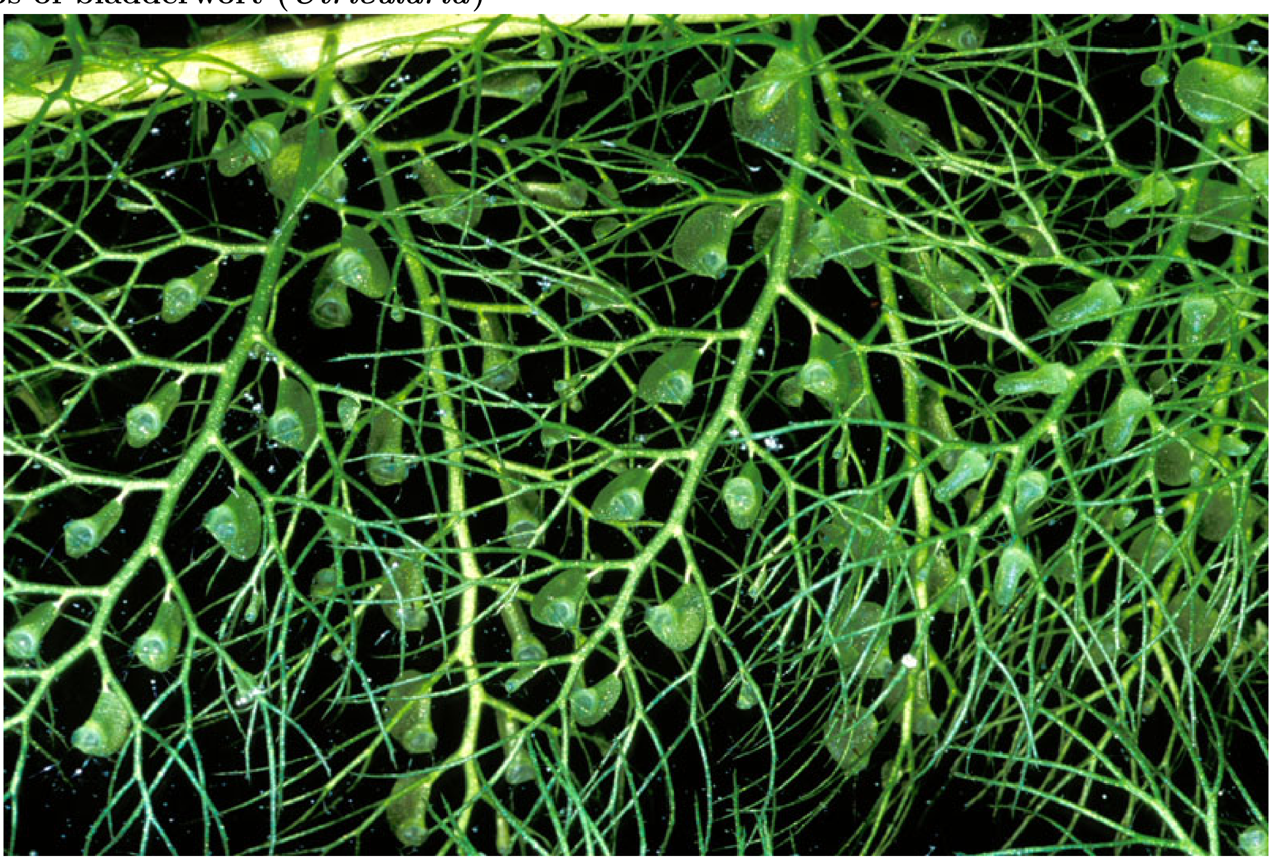




Thorns

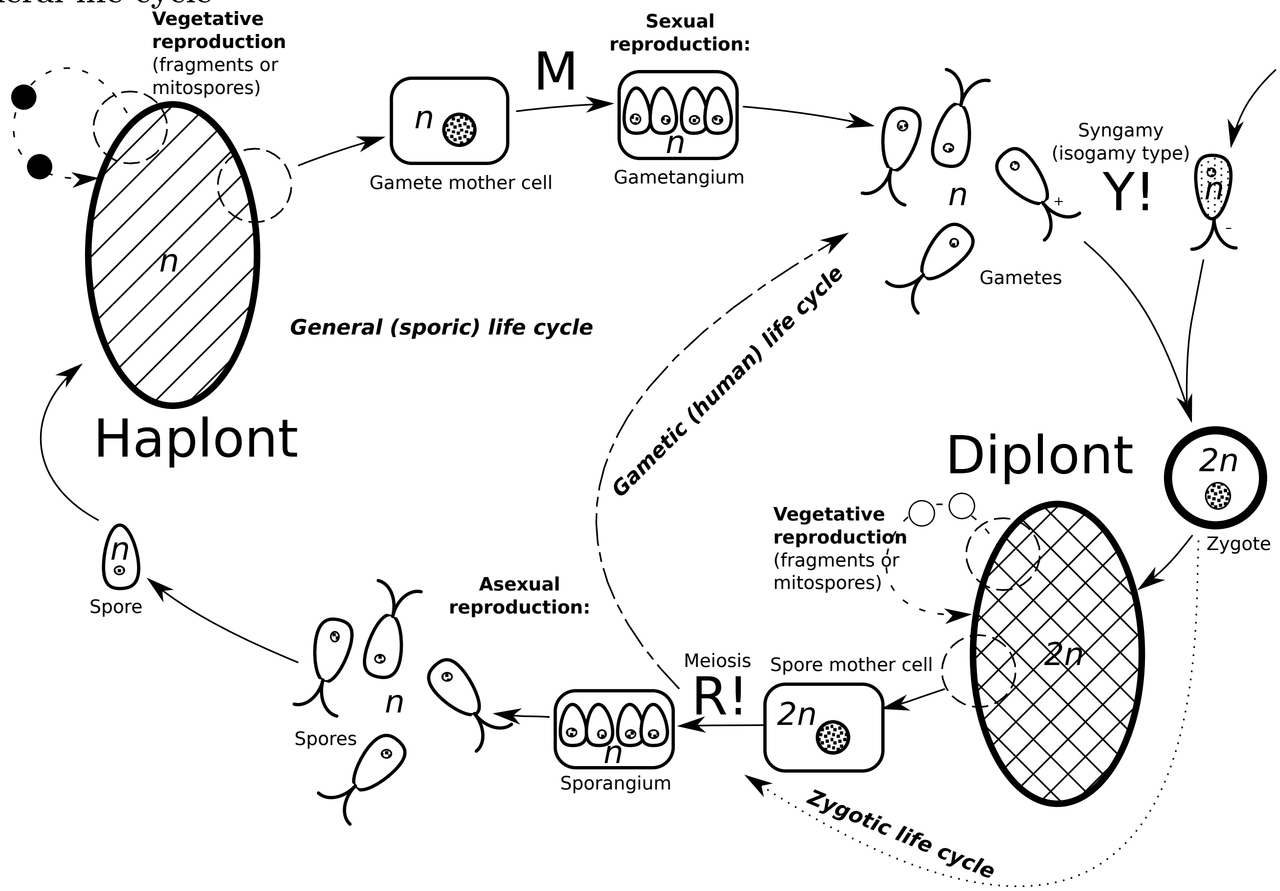
Cladophylls: leafy stems

Traps of bladderwort (*Utricularia*)

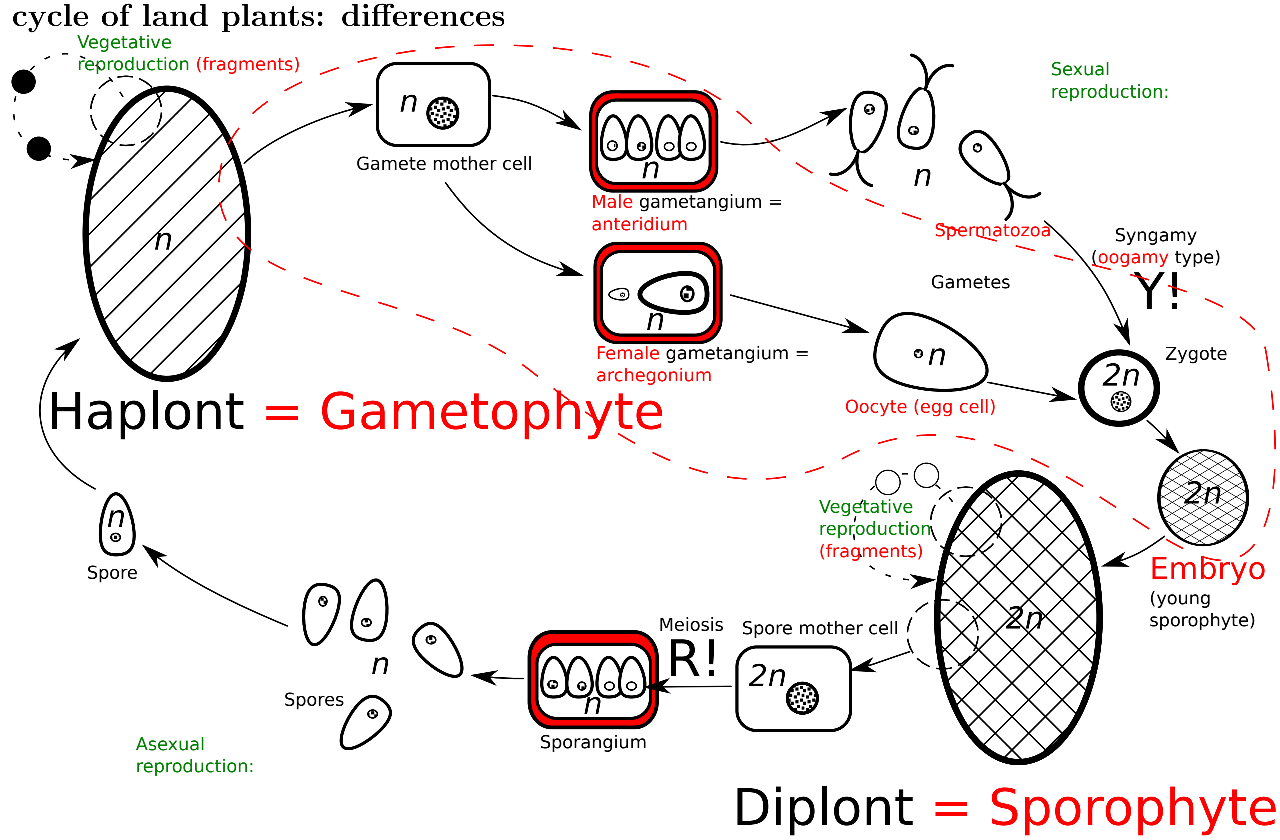


48.6 Origin of seed

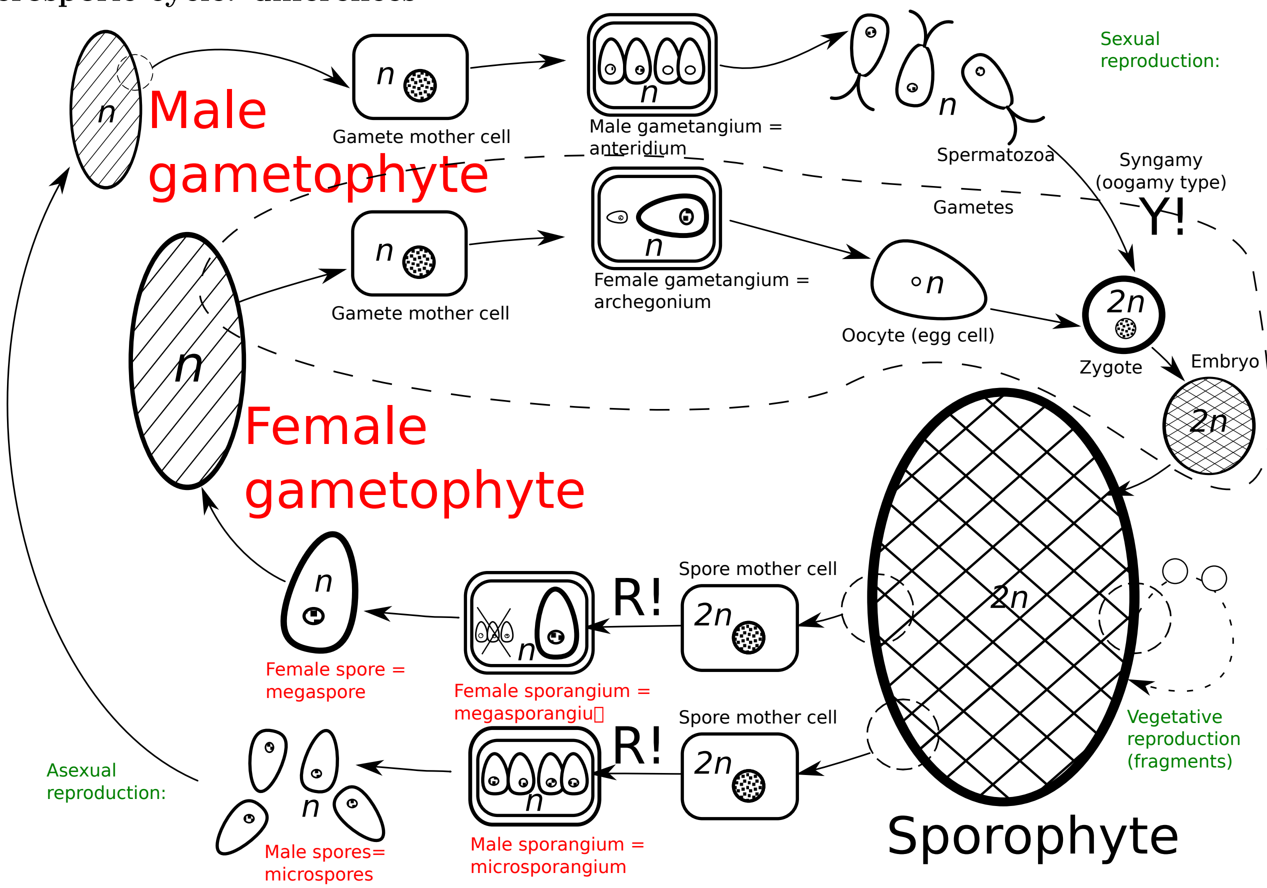
General life cycle



Life cycle of land plants: differences



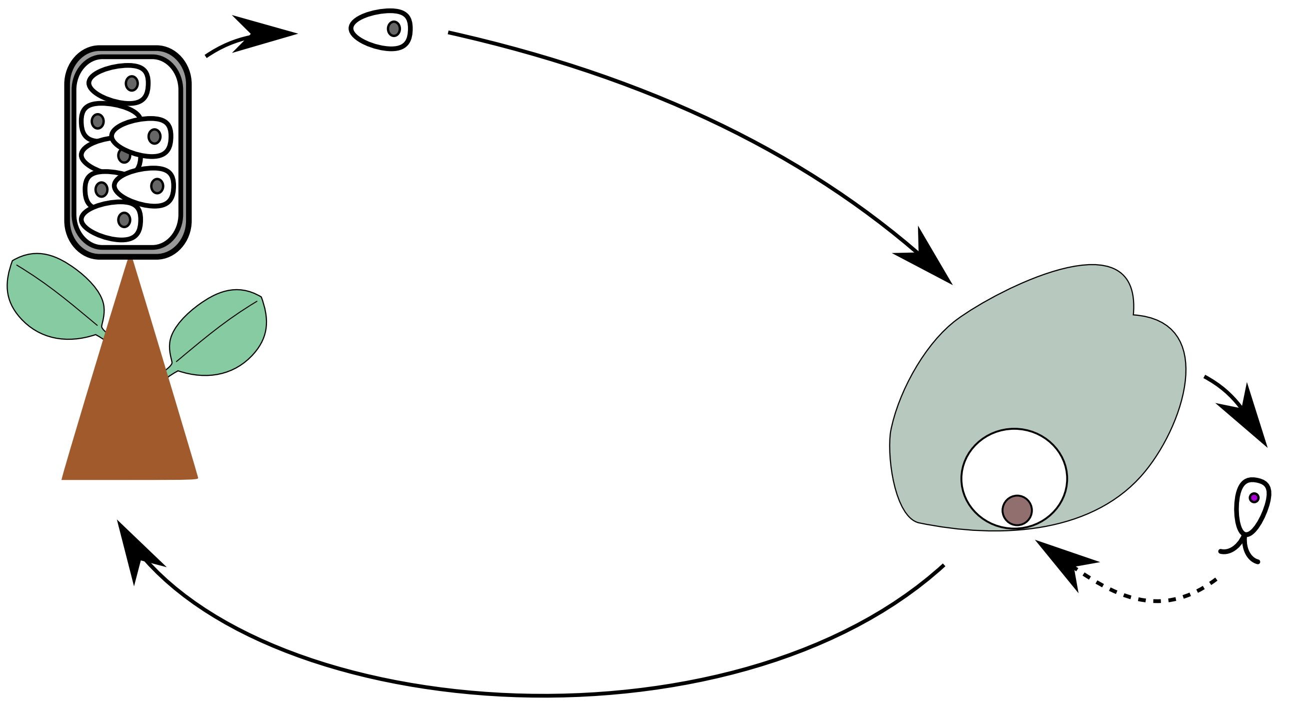
Heterosporic cycle: differences



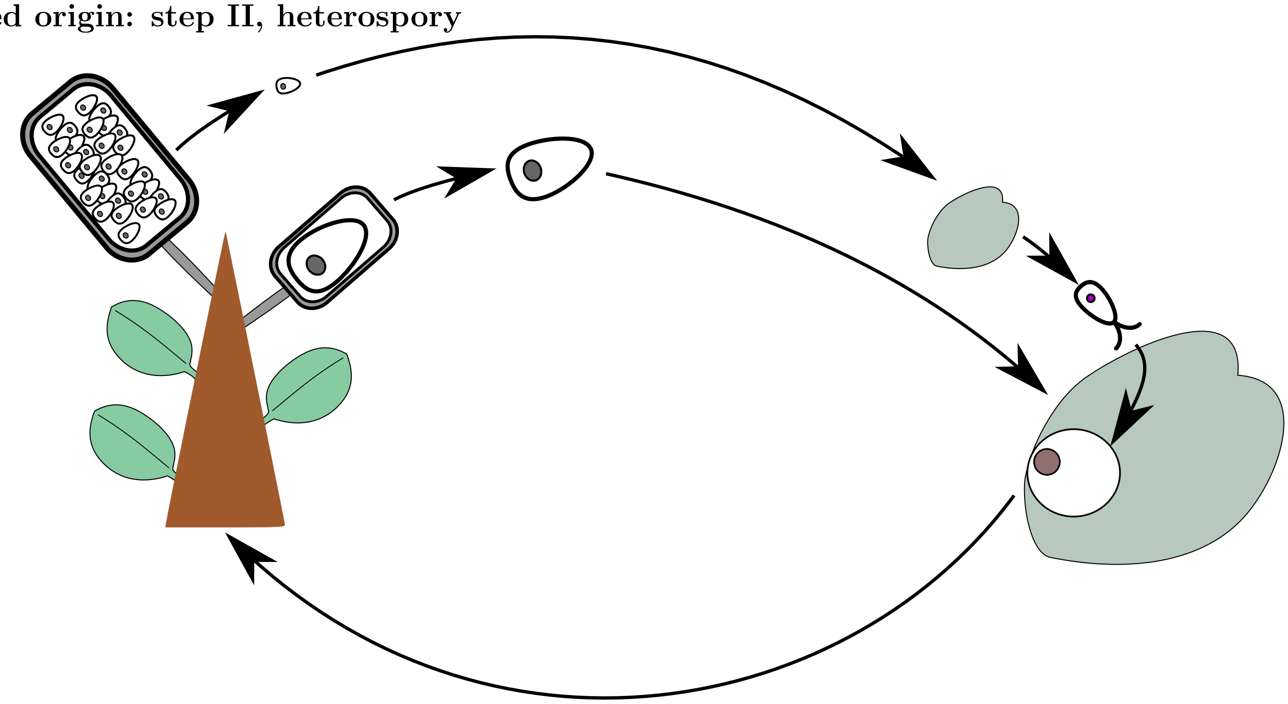
Origin of seed

- **"Dinosaur problem":** without control on the r-strategic gametophyte, K-strategic tree sporophyte cannot guarantee its reproduction
- **Seed is the result of enforced control of sporophyte over gametophyte**
- Growing of gametophytes, syngamy (fertilization) and growing of daughter sporophyte—everything happens **directly on mother sporophyte**

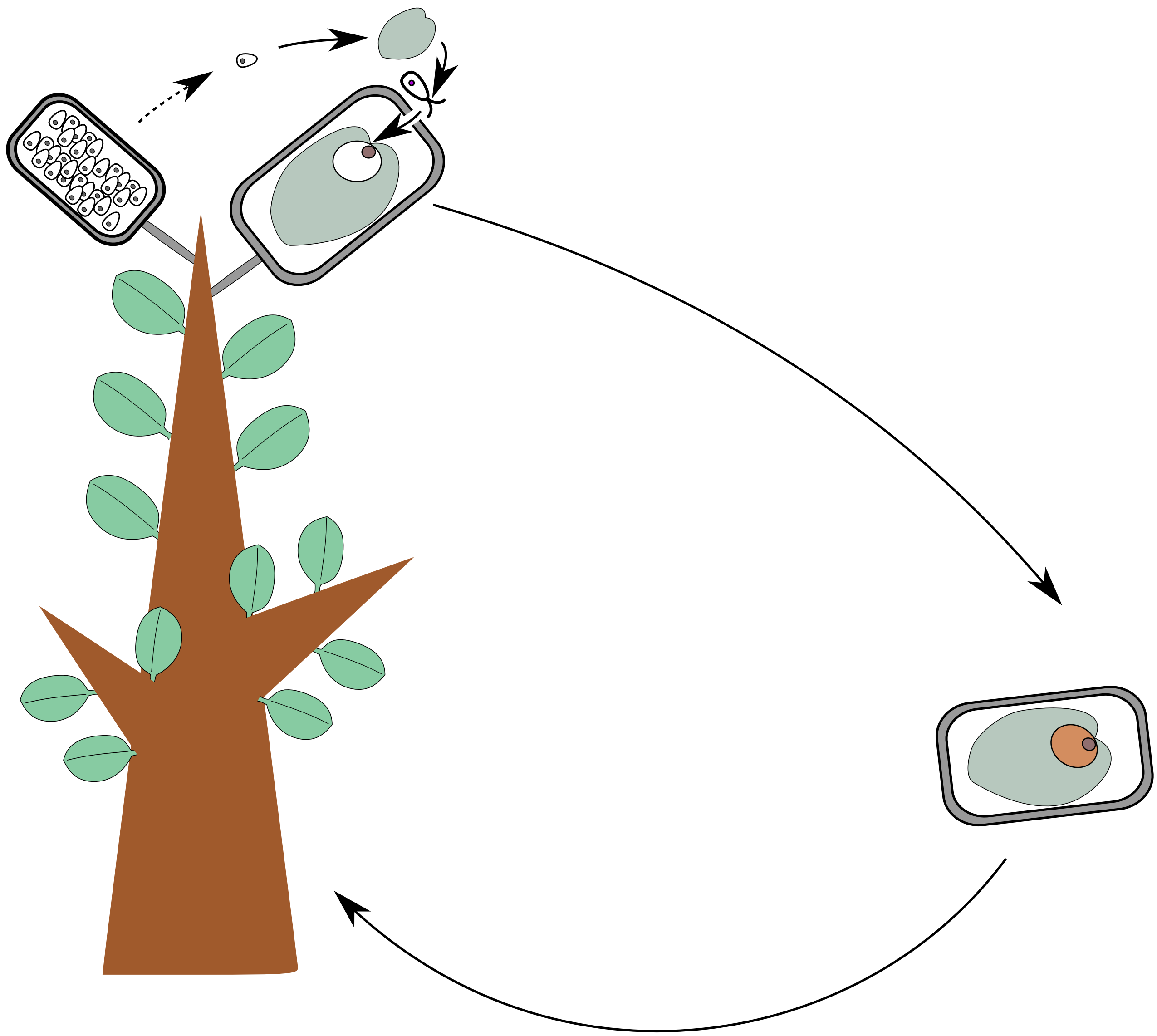
Seed origin: step I, homospory



Seed origin: step II, heterospory



Seed origin: step III, seed

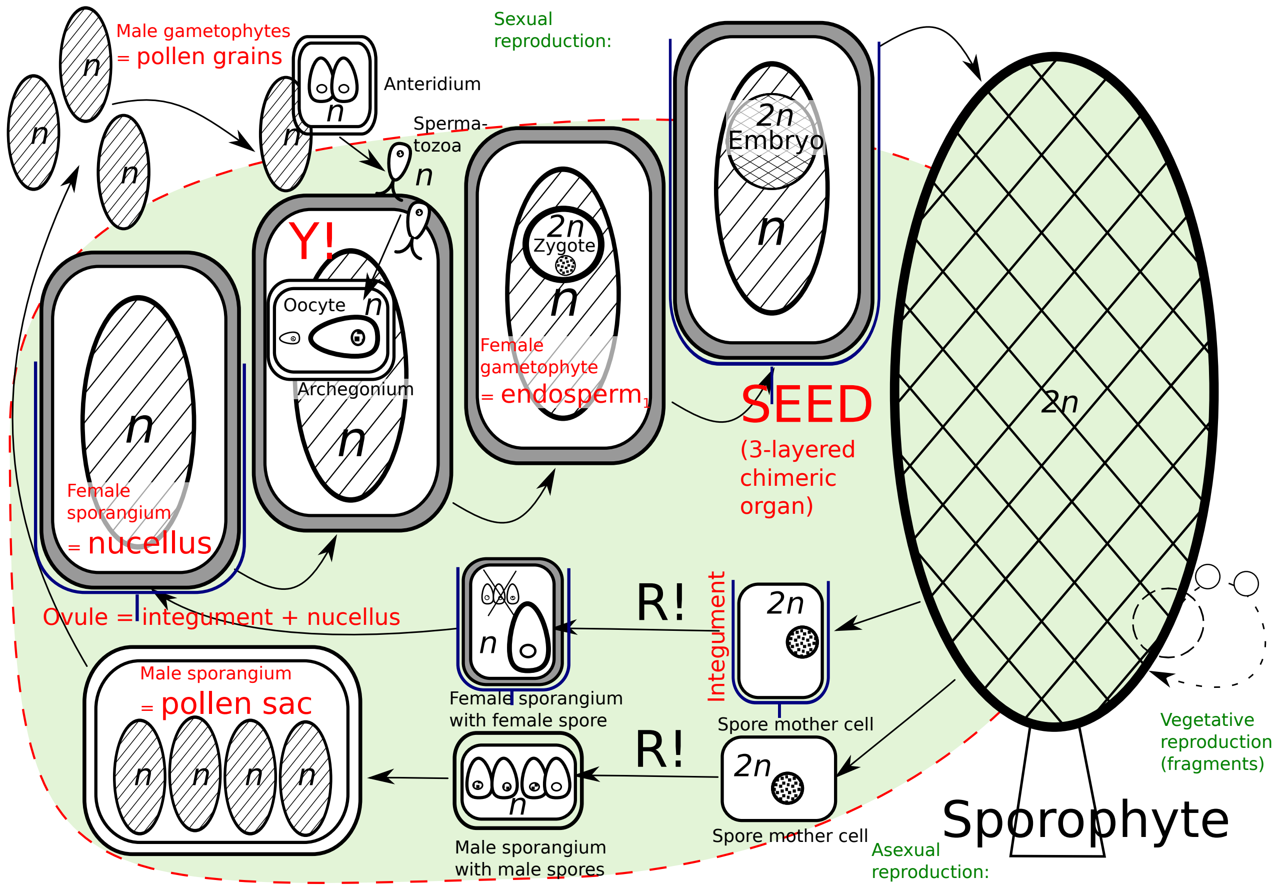


Seed plants have life cycle where almost all stages happen on mother sporophyte

Terms covered:

- Ovule and integument
- Nucellus and pollen sac
- Pollen grains and endosperm
- Seed

Seed plant cycle: differences



Summary: the seed

- Seed is a **chimeric organ** with three layers: (1) mother sporophyte tissue (integument + nucellus), (2) female gametophyte tissue (endosperm) and (3) daughter sporophyte (embryo)
- Biggest disadvantages of having seed are: (a) low probability of fertilization (pollination needed) and (b) overall slowness of cycle
- "Hot spots" of seed life cycle: (1) pollination with wind, insects or anything, (2) fertilization with **pollen tube** and (3) reduction of gametophytes

For Further Reading

References

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

Outline

49 Seed plants

49.1 Diversity of seed plants

Spermatophyta: seed plants

- ≈ 1000 species of non-angiosperms and $\approx 250,000$ species of angiosperms (99.6% of seed plants)
- Sporic life cycle with sporophyte predominance and **seed**
- Gametophyte is reduced to cells inside ovule or inside pollen grain. Minimum number of cells is 3 for male gametophyte (pollen grain) and 4 for female gametophyte (embryo sac of angiosperms). Antheridia are reduced. In angiosperms and Gnetopsida, archegonia are also reduced.
- Sporophyte always starts development from embryo located inside nutrition tissue, endosperm$_1$ (female gametophyte) or endosperm$_2$ (second embryo)
- Have axillary buds
- Homoiohydric plants (same as ferns)
- Have secondary thickening

Spermatophyta classes

- **Ginkgoopsida**, ginkgo class
- **Cycadopsida**, cycads
- **Pinopsida**, conifers
- **Gnetopsida**, gnetophytes or chlamydosperms
- **Angiospermae**, or Magnoliopsida, flowering plants

Ginkgoopsida

- Smallest class, only one species (!), Chinese tree *Gigkgo biloba* which became extinct several thousand years ago but saved as a "church tree".
- Distinctive triangle-shaped leaves with dichotomous venation
- Ovules are solitary or paired; microsporangia are in catkin-like structures; has sexual chromosomes (!)
- Pollen grains produce two mutli-flagellate spermatozoa which swim to large oocyte
- Seeds are fruit-like (generally edible), become ripe laying on a ground for a long time
- Almost no phytophagous insects damage *Ginkgo* leaves; the fungal symbiont of *Ginkgo* also belongs to separate class inside basidiomycetes, Bartheletiomycetes.

***Ginkgo biloba* ovules**

***Ginkgo biloba* male organs**

Ginkgo biloba seeds

Cycadopsida

- Two families, dozen genera and ≈ 300 species distributed mostly in tropics
- Palm-like plants, with large (and usually very rigid) pinnate leaves
- Stem structure is not similar to conifers and *Ginkgo*; cycads have large pith and anomalous secondary thickening via multiple cambium rings
- Ovules are attached to modified leaves (sporophylls) and usually gathered in large upright cones; microsporangia are always in cones
- Also have multi-flagellate spermatozoa, archegonia and large oocyte
- Large seeds are animal-distributed; life cycle is extremely slow (several years from initiation of cone to germination of seed).

Cycadopsida families

- Two families, sometimes even placed in different orders:
  - Cycadaceae, whith only genus *Cycas*. They do not have female cones, ovules are attached to leaves which are not radically modified. Leaves have fiddleheads (same in ferns!).
  - Zamiaceae, with all other genera (*Zamia integrifolia* is native to USA). Have female cones.

***Cycas* sp.: young leaflets form fiddleheads**

Male *Cycas* sp. in dry season

***Cycas* sp. seeds**

Encephalartos gratus (Zamiaceae)

Zamia integrifolia **(Zamiaceae)**

49.2 “Higher” seed plants

Spermatophyta classes

“Lower”:

- **Ginkgoopsida**, ginkgo class
- **Cycadopsida**, cycads

“Higher”:

- **Pinopsida**, conifers
- **Gnetopsida**, gnetophytes or chlamydosperms
- **Angiospermae**, or Magnoliopsida, flowering plants

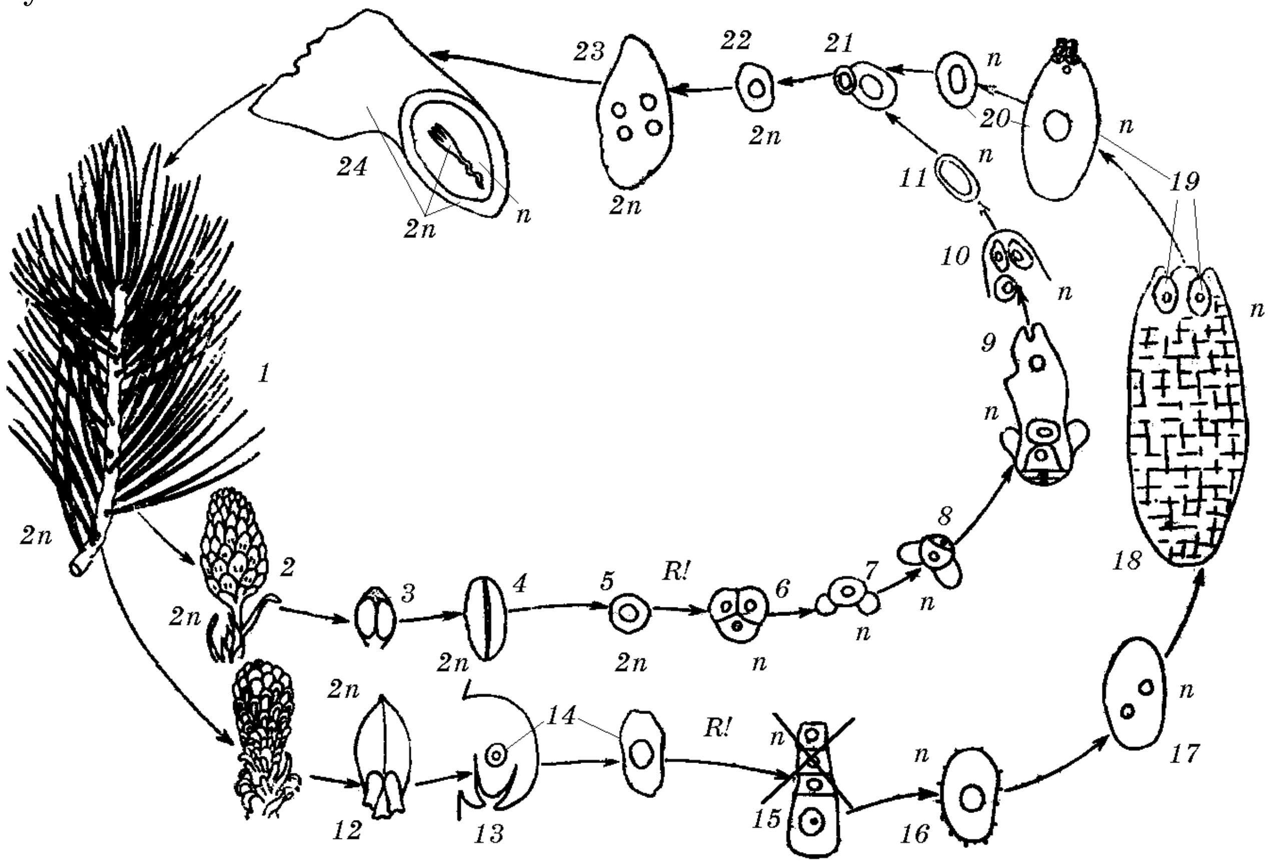
49.3 Conifers

Pinopsida

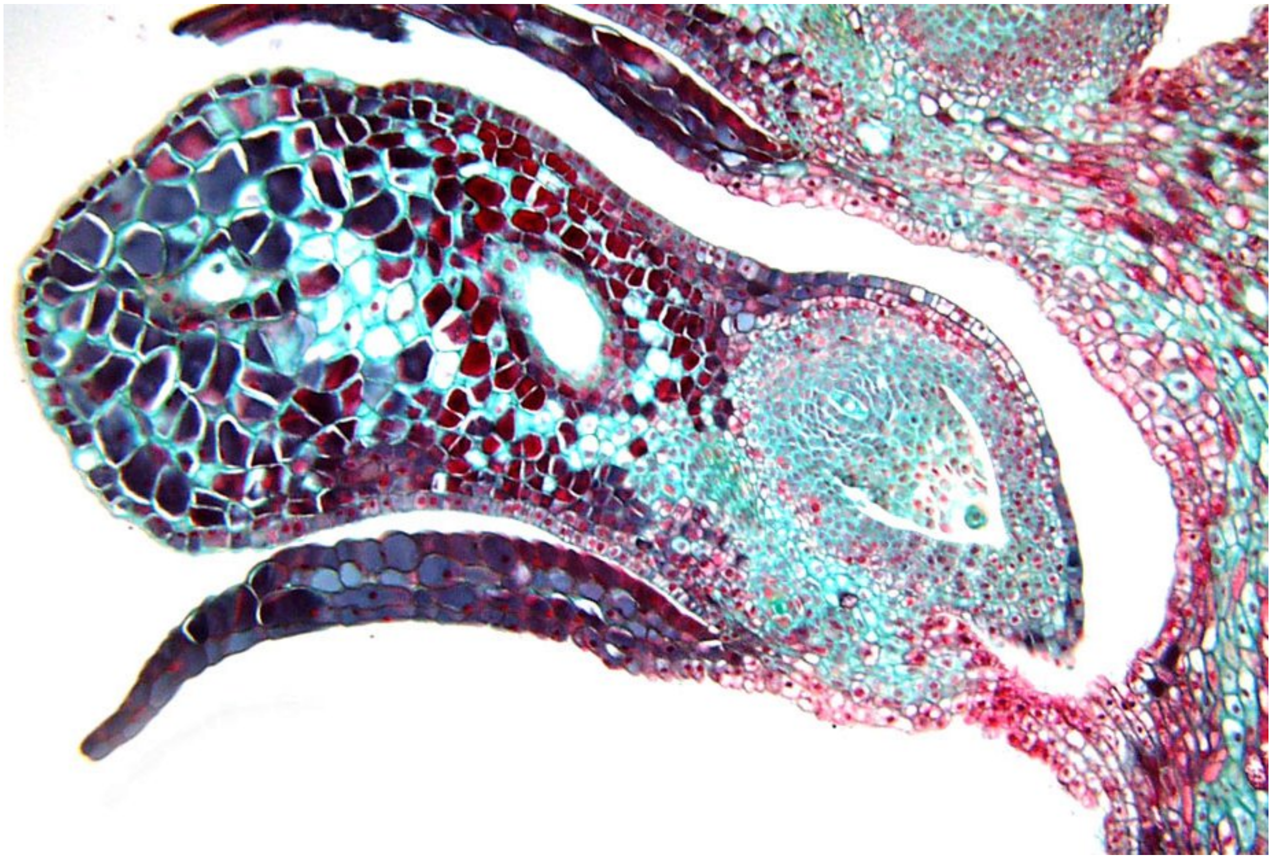
- Three orders, several families and ≈ 600 species
- Mostly temperate evergreen trees, but some are deciduous (like *Larix*, *Pseudolarix*, and part of Cupressaceae)

- Stem with large amount of xylem, relatively small cork and minute pith
- Ovules are always attached to specialized leaves (seed scales) and together with bract scales they are compacted in cones; microsporangia are attached to microsporophylls and also occur in cones of simpler structure
- Male gametes without flagella (spermatia), consequently, pollen grains grow into **pollen tubes**
- Female gametophyte is more reduced than in cycads and *Ginkgo*
- Seeds are wind- and animal-distributed, life cycle shorter but still up to two years

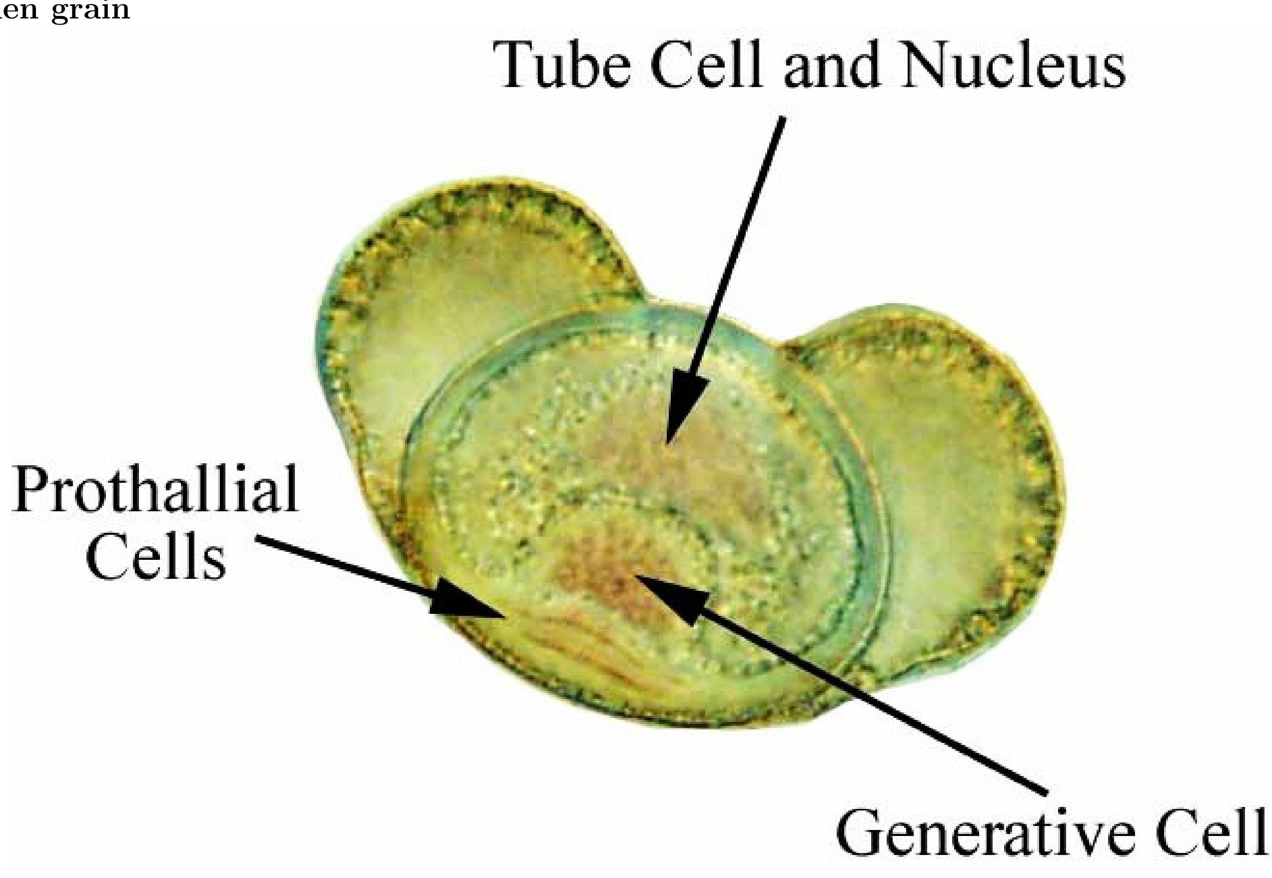
Life cycle of conifers: another view



Bract scale, seed scale and ovule



Pollen grain



Pinopsida orders and families

- Pinales
  - **Pinaceae**.
- Araucariales—grow mostly in tropics or in South Hemisphere.
  - Araucariaceae
  - Podocarpaceae
- Cupressales
  - Sciadopityaceae
  - Cupressaceae (incl. Taxodiaceae)
  - Cephalotaxaceae
  - Taxaceae

Pinaceae

- Have resin and needle-like leaves, often in shortened shoots, **brachyblasts**. Large cones with paired (seed and bract) scales.
- Biggest conifer family, include large genus *Pinus* (pine) and other genera like *Larix* (larch), *Cedrus* (cedar), *Picea* (spruce), *Abies* (fir) etc.

Cupressaceae and Taxaceae

- **Cupressaceae**—cypress family. No resin. Cones are small, with fused bract and seed scales. Leaves are dimorphic, needle-like and scale-like. Part of genera (formerly belong to Taxaceae family) are deciduous but with branches instead of leaves. Genera: *Cupressus* (cypress), *Juniperus* (juniper), *Taxodium* (bald cypress), *Sequoia* (coastal red cedar), *Sequoiadendron* (mountain red cedar), *Metasequoia* etc.
- **Taxaceae**—yew family. Female cones are modified in berry-like structures with one enlarged red scale. Leaves are needle-like. No resin. *Taxus* (yew) provides famous reddish-brown, springy wood.

Pseudolarix amabilis (Pinaceae), spring

***Sequioa sempervirens* (Cupressaceae)**

***Taxus baccata*, Taxaceae**

49.4 Gnetophytes

Gnetopsida

- Small class of only three genera (*Ephedra*, *Welwitschia*, *Gnetum*), which are so different that botanists place them in different orders (and sometimes even subclasses).
- Tropical trees (*Gnetum*) or desert shrubs (*Ephedra*) or nobody-knows-what (*Welwitschia*)
- Stem structure is similar to conifers but *Gnetum* and *Welwitschia* have vessels (like angiosperms)
- Ovules are solitary, **covered with additional outer integument** (however, **this is not a pistil** because micropyle come out of this cover)
- Male gametes are spermatia, have pollen tube and **no archegonia** in *Gnetum* and *Welwitschia* (like in angiosperms). Multiple fertilization an polyembryony is widespread, *Ephedra* and *Gnetum* even has a double fertilizarion (like angiosperms). Only one embryo survives, other are eaten (endosperm$_2$). Also have endosperm$_1$ (female gametophyte).
- *Welwitschia* is insect-pollinated, other are wind-pollinated like most non-angiosperms.
- Seeds are animal-dispersed (except *Welwitschia*).
- Amazingly, molecular data show relations with conifers, not with angiosperms!

Gnetum

- Tropical shrubs, vines or small trees (30–35 species) with opposite leaves with pterodromous venation (like angiosperms again!). However, investigation of leaf development showed that initially leaf had dichotomous venation (like *Ginkgo* and some conifers).
- Dioecious plants, male and female structures (fructifications) are catkin-like
- Seeds big, colored

***Gnetum* seeds**

***Gnetum* female fructifications**

***Gnetum* male fructifications**

Welwitschia

- One species occurring in Namibian desert (South Africa)
- Life form is completely unusual, the best description is "overgrown seedling": small trunk with only two (constantly growing on the basement and degrading on top) wide leaves with parallelodromous venation. Secondary thickening anomalous (like in cycads). Wood with vessels.
- Insect-pollinated (!) dioecius plants
- Fructifications are cone-like; male one is similar to flower and contain sterile ovule (!)
- Seeds are wind-dispersed

Welwitschia

Welwitschia

***Welwitschia* female cones**

***Welwitchia* male cones**

***Welwitchia* pollinators: *Odontopus sexpunctulatus* bug**

Ephedra

- $\approx$ 35 species growing in dry places across all North Hemisphere and also in South America
- Shrubs or small trees, leaves are usually reduced to scales, stems are articulate (like horsetails). Wood is similar to conifers.
- Plants are monoecoius or dioecious, male and female (bisexual also occur) fructifications are short, covered with thick scales
- Wind-pollinated, animal dispersed
- *Ephedra sinensis* is a source of pharmaceutically important **ephedrine**
- In all, *Ephedra* is more primitive than two other genera of Gnetopsida: wood does not contain vessels, ovule has large archegonia

Ephedra

***Ephedra nevadensis*, female fructification**

***Ephedra nevadensis*, male fructification**

Ephedra **seeds**

49.5 Flowering plants

Flowering plants are "Spermatophyta 2.0"

- Reduction of gametophyte: 3-celled pollen and 7-celled embryo sac
- No archegonia and anteridia
- Spermatia, pollen tube
- Double fertilization
- New endosperm (second embryo)
- Cupule (pistil) and fruit
- In general, **angiosperms have accelerated life cycle** needed for fast-growing herbs

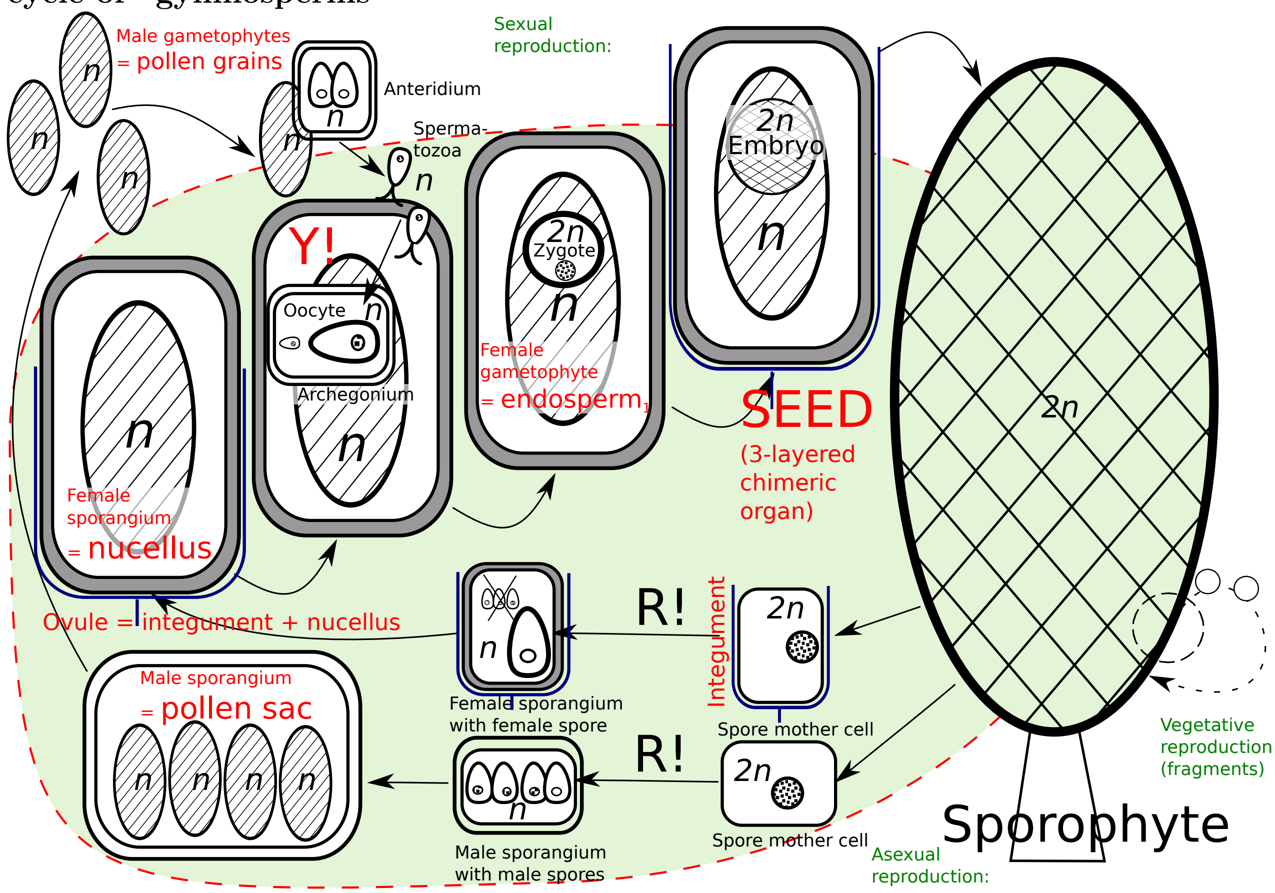
Note: angiosperms = flowering plants = class Magnoliopsida

Life cycle of angiosperms

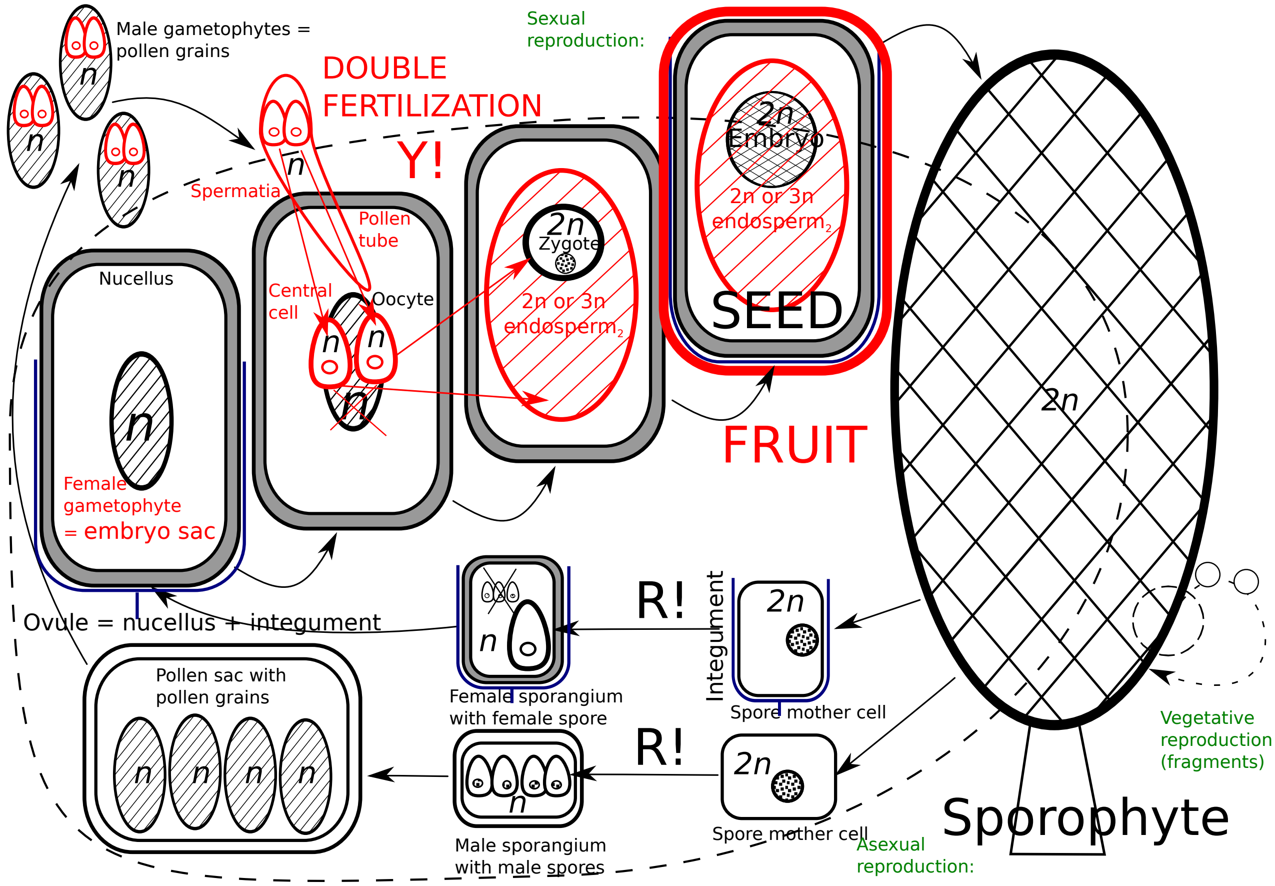
Terms covered:

- Embryo sac, central cell
- Spermatia (sperms without flagella), pollen tube
- Double fertilization
- Pistil and ovule → fruit and seed

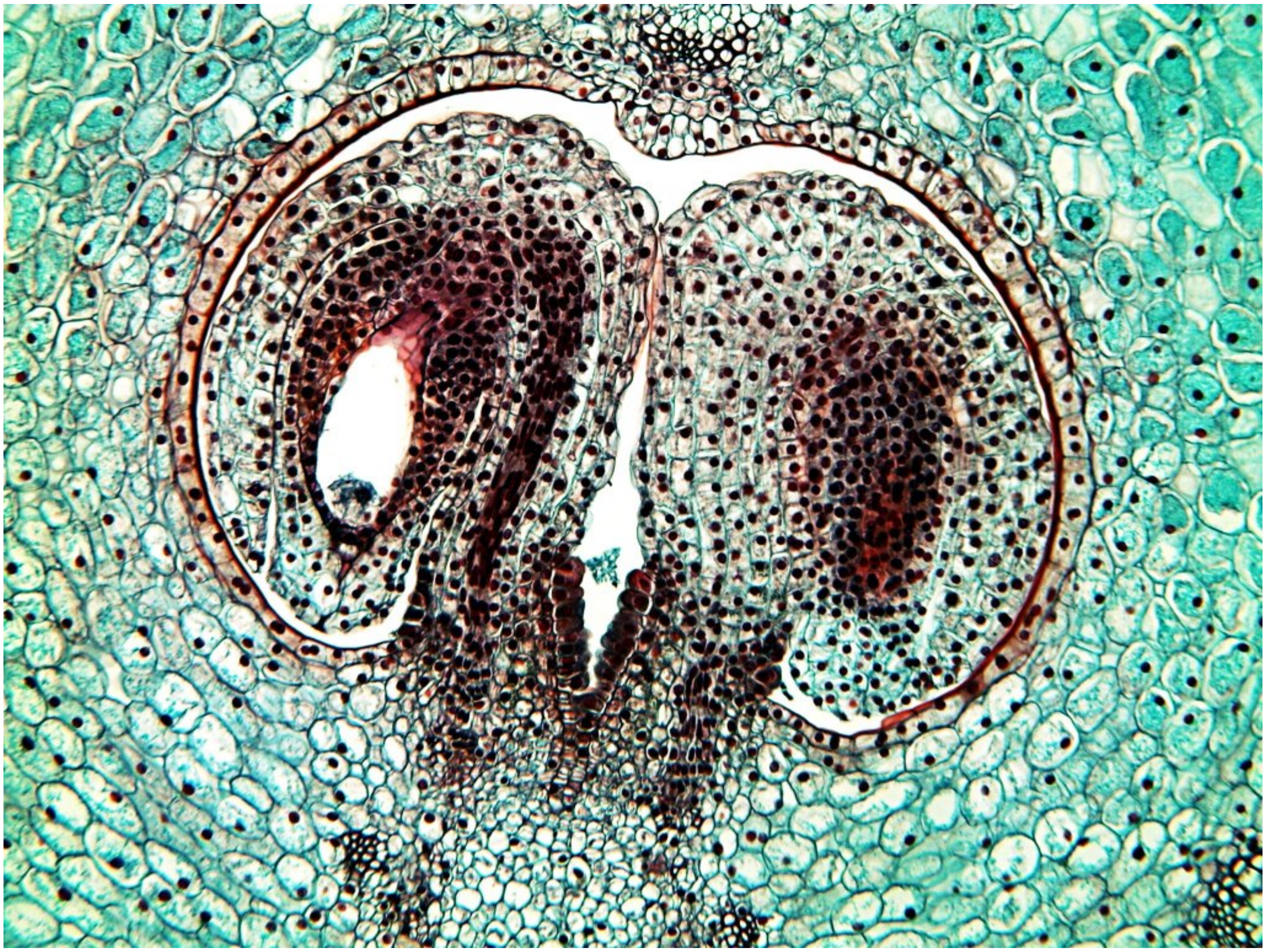
Life cycle of "gymnosperms"



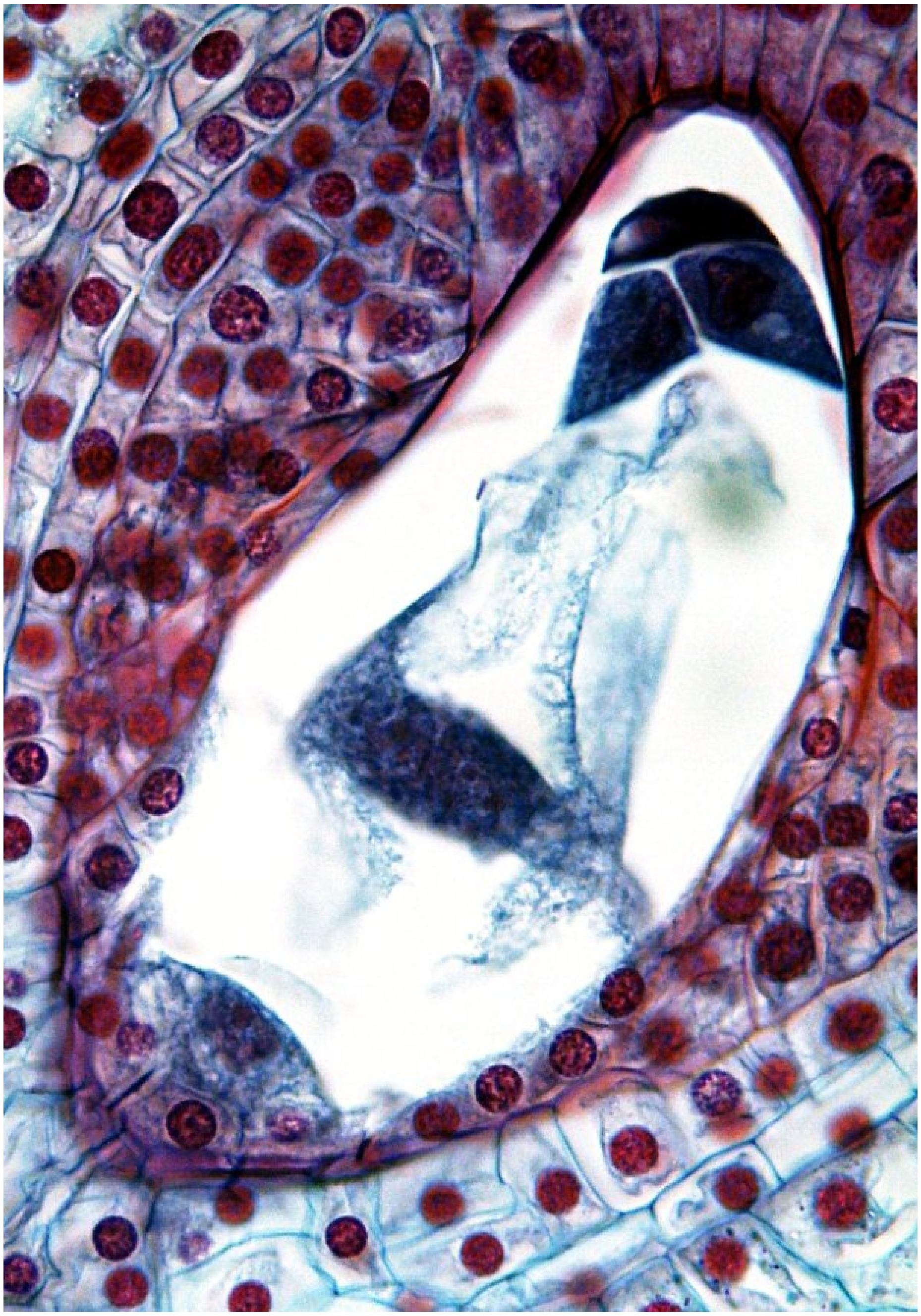
Life cycle of angiosperms: differences



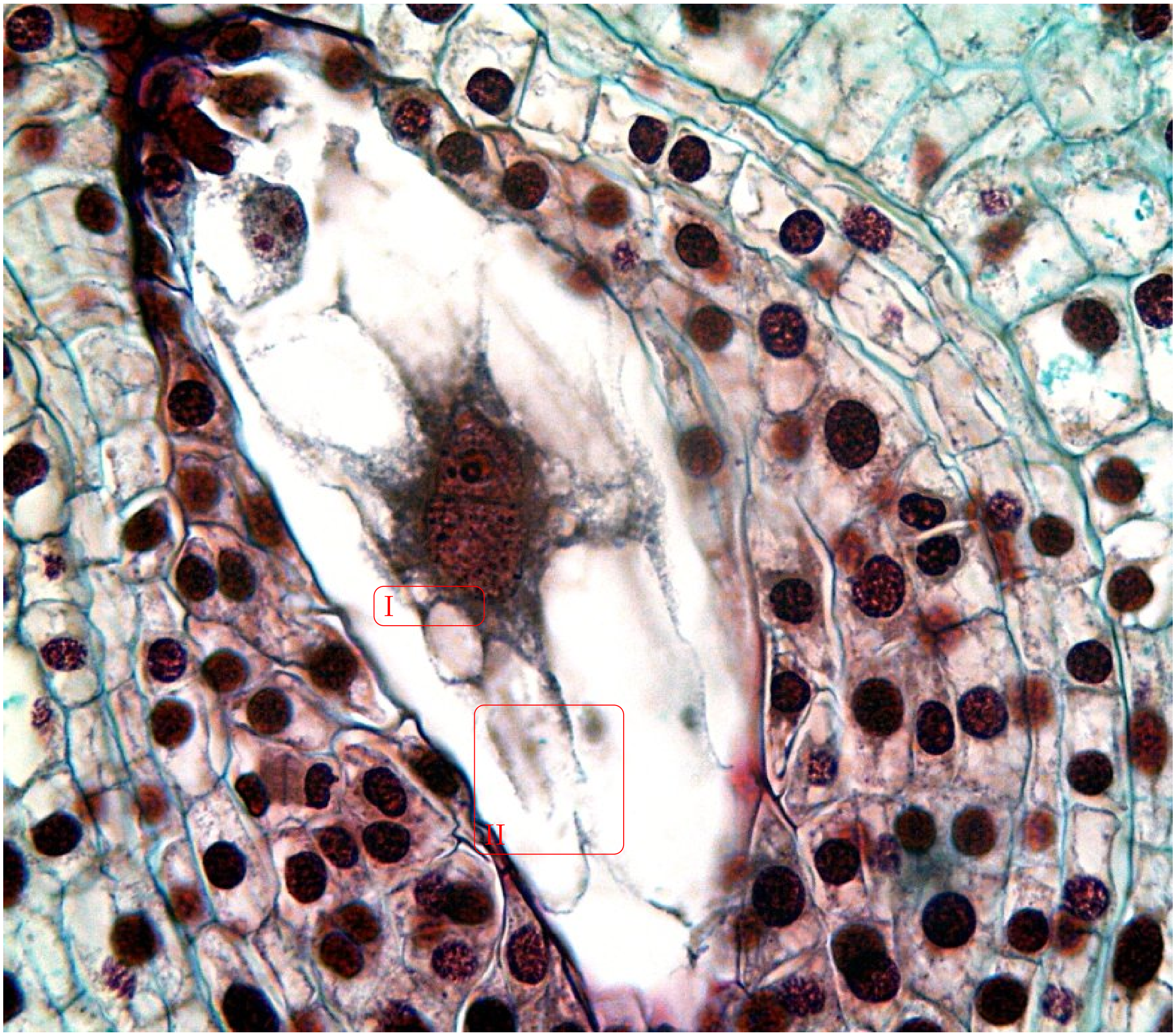
Ovules (*Lilium* sp., lily)



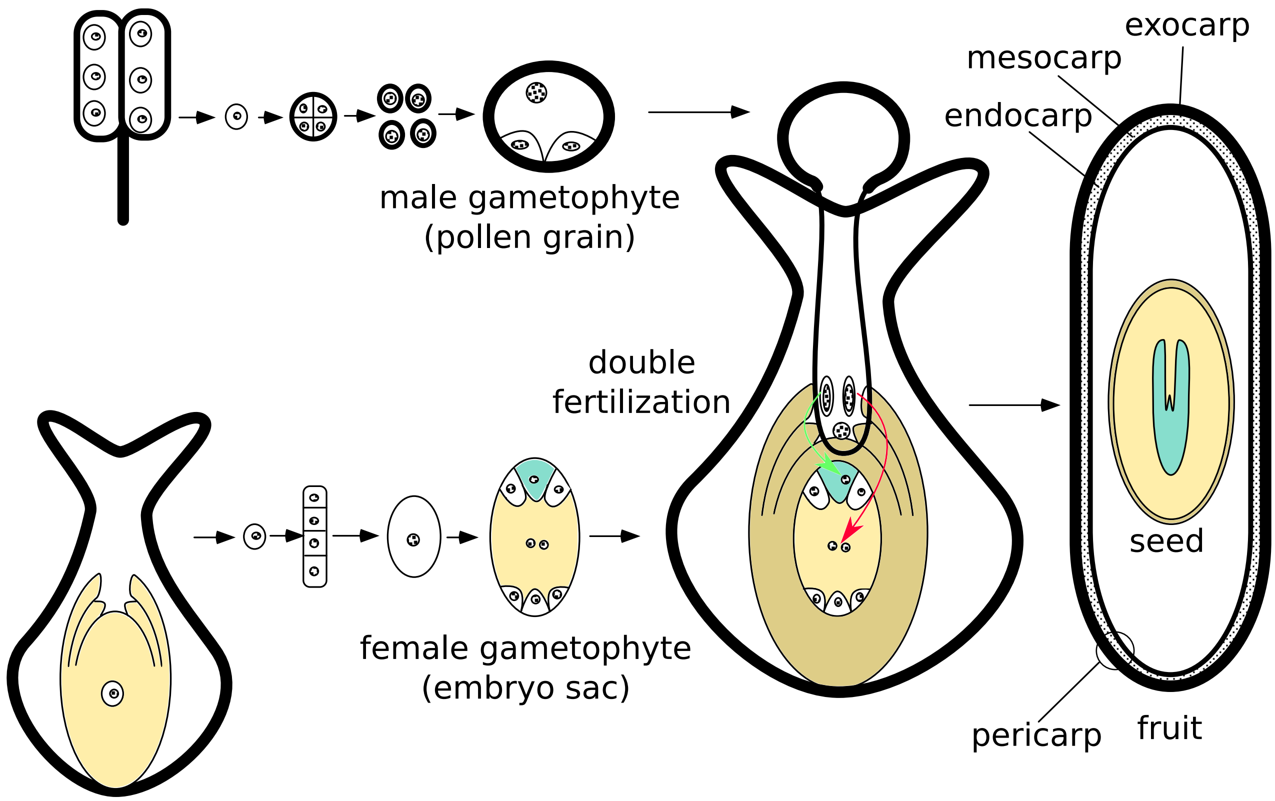
Embryo sac (*Lilium* sp., lily)



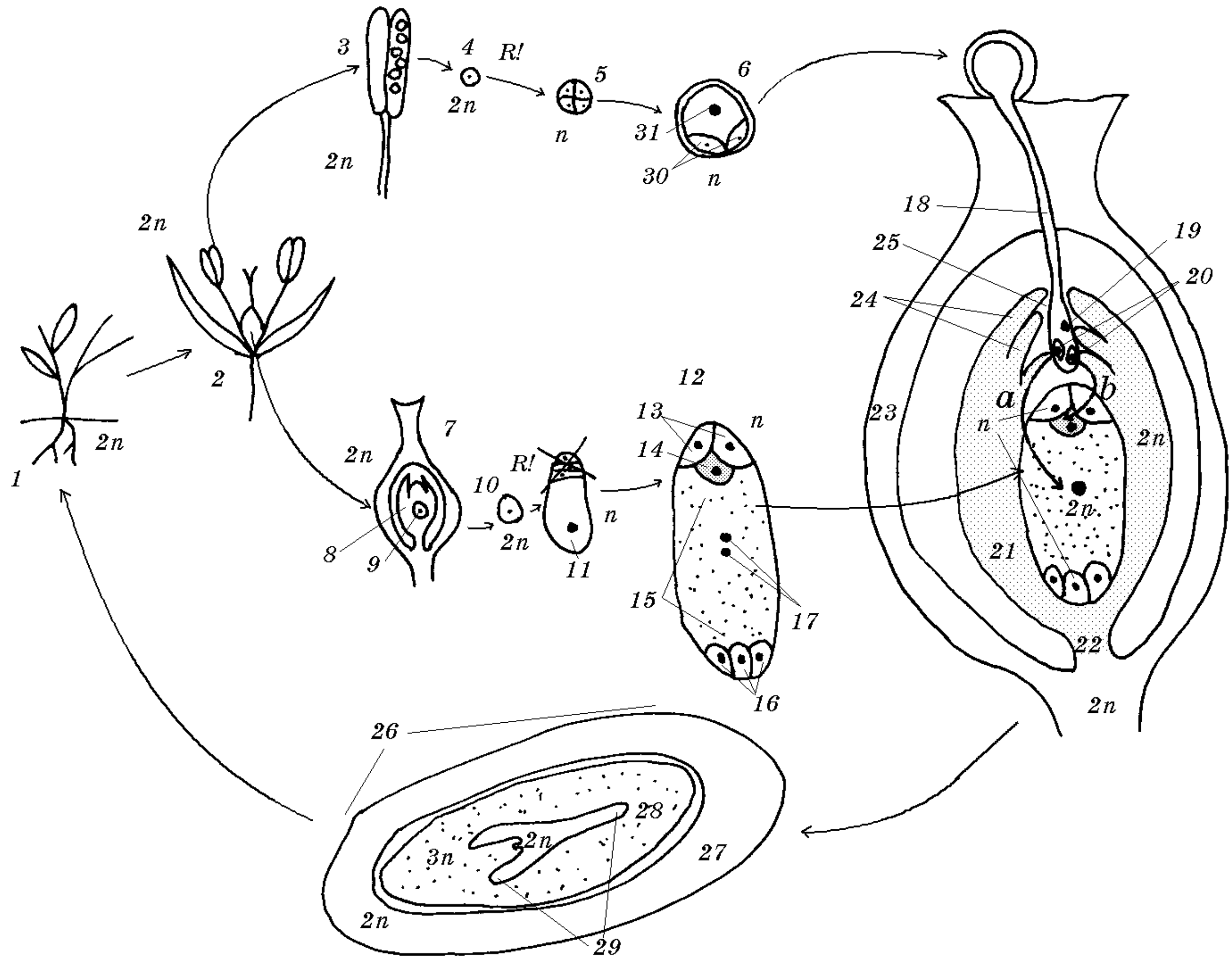
Double fertilization (*Lilium* sp., lily)



Angiosperms: relations between structures



Life cycle of angiosperms: another view



49.6 Class Magnoliopsida, or Angiospermae

Angiosperms in general

- Names: Magnoliopsida, Angiospermae ("angion" is a "bottle"), angiosperms, flowering plants
- 250,000 species, more than 90% of all plants diversity, the diversity is comparable with mollusks (200,000) and arthropods ($\approx 1,000,000$) and much more than fungi (75,000) and vertebrates (30,000)
- $\approx$ 300 families and $\approx$ 40 orders
- Grow everywhere except open ocean and central Antarctic

Diagnostic characters of angiosperms

- Flower
- Angiospermy
- Stigma
- Double fertilization:

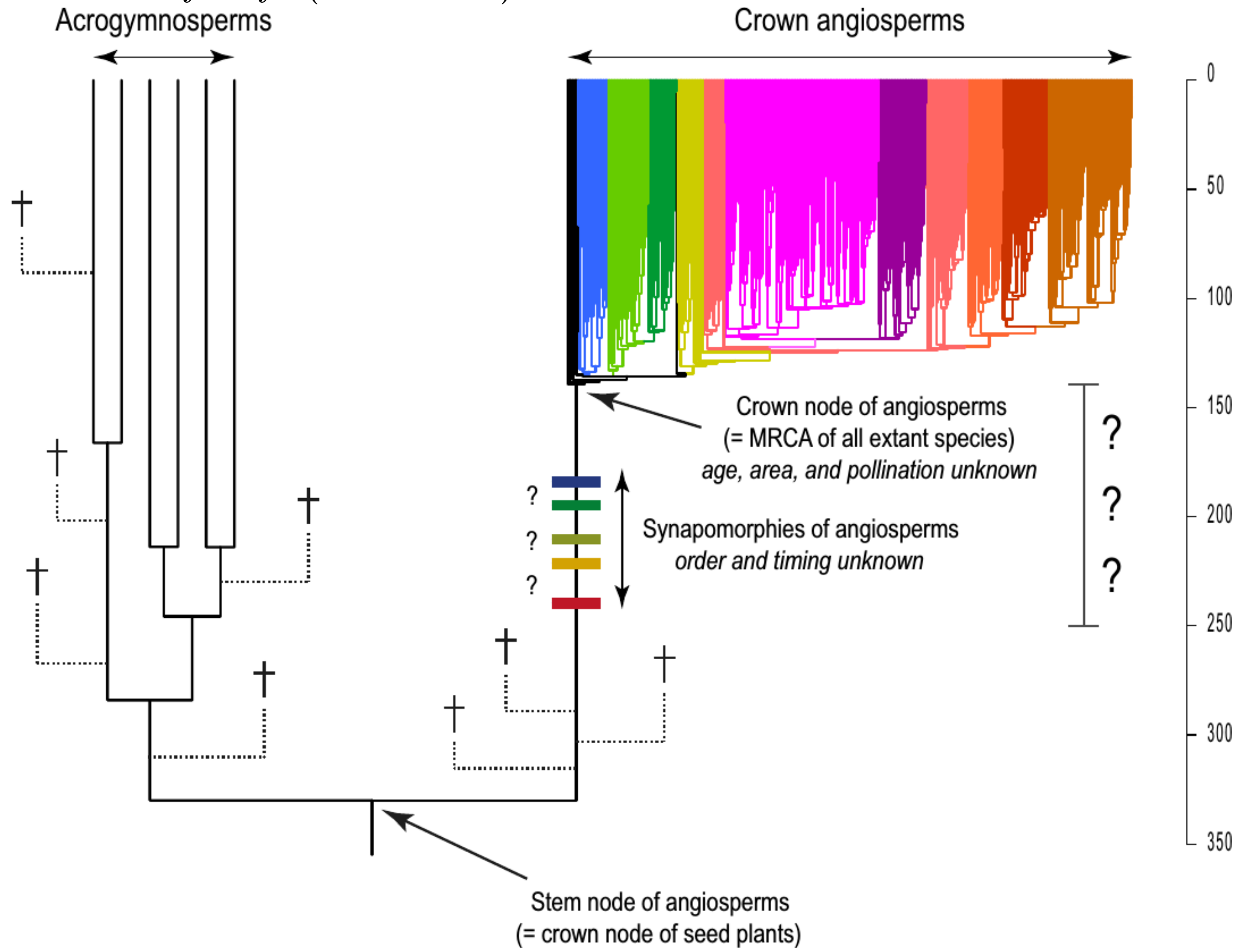
- 1st sperm cell (1st spermatium, n) + egg cell (n) = zygote ($2n$)
- 2nd sperm cell (2nd spermatium, n) + central cell ($2n$ or sometimes n) = mother cell of endosperm$_2$ ($3n$ or sometimes $2n$)

Second fertilization is a **signal** that first fertilization has been occurred. Endosperm$_2$ develops from the "signalized" female gametophyte.

- Fruit
- Parcellation

In all, any of these characters taken alone is not unique, but together they delimit the group

"Abominable mystery" (Ch. Darwin)



Whereas angiosperms are not unique, their origin is still obscure.

49.7 Flower

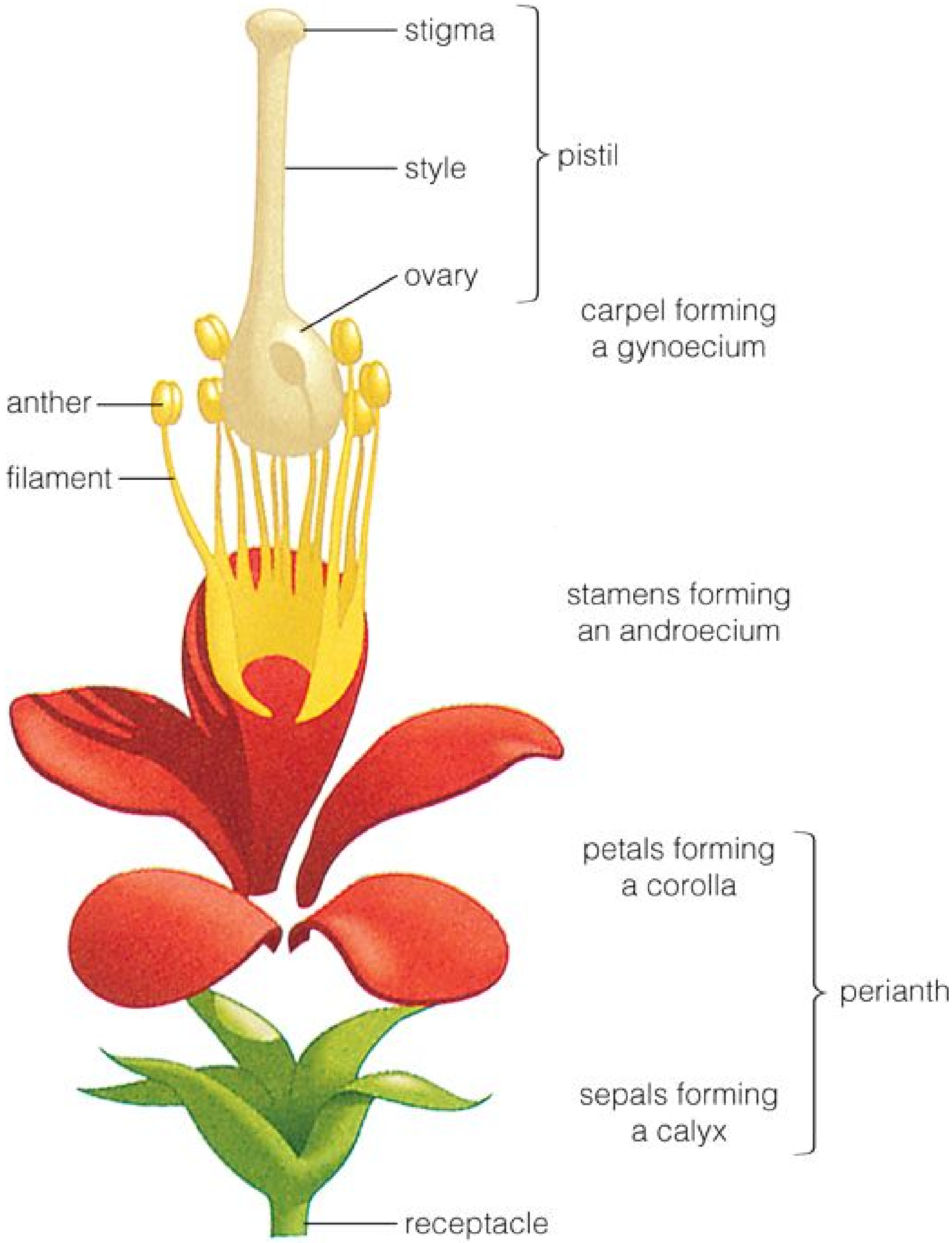
Definition of flower

- Compact generative shoot (= floral unit, FU) with three zones
- Three main zones: sterile (perianth), male (androecium) and female (gynoecium)
- General characters: sex, merosity, symmetry, position of gynoecium

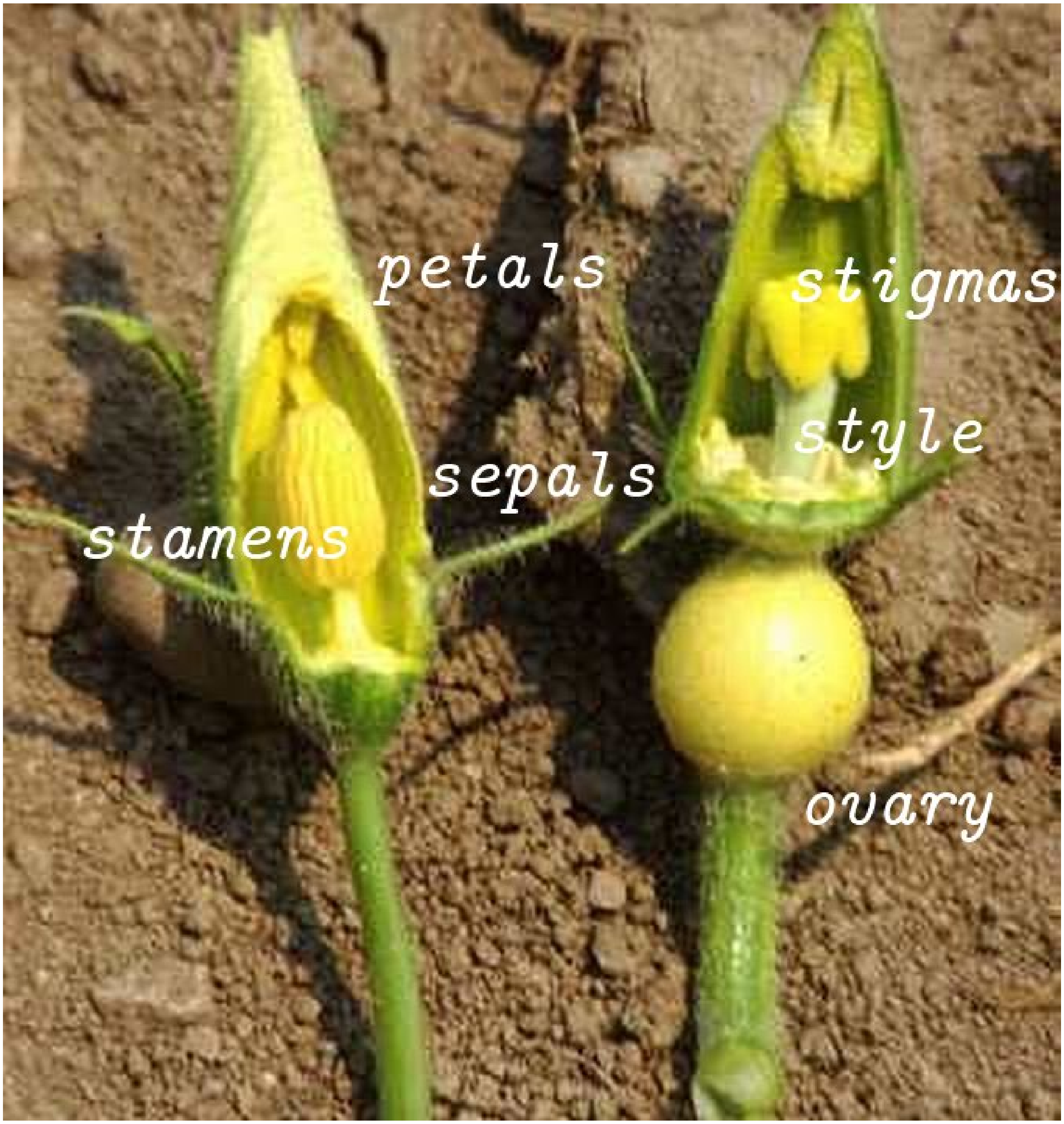
Structure of flower

- Perianth (consists of tepals)
  - Frequent case: double perianth
    - Calyx (consists of sepals)
    - Corolla (consists of petals)
- Androecium (consists of stamens)
  - Filament
  - Anther (consists of pollen sacs)
- Gynoecium (consists of pistils)
  - Ovary (consists of carpels)
  - Style
  - Stigma

Structure of flower



Pumpkin (*Cucurbita pepo*) flower

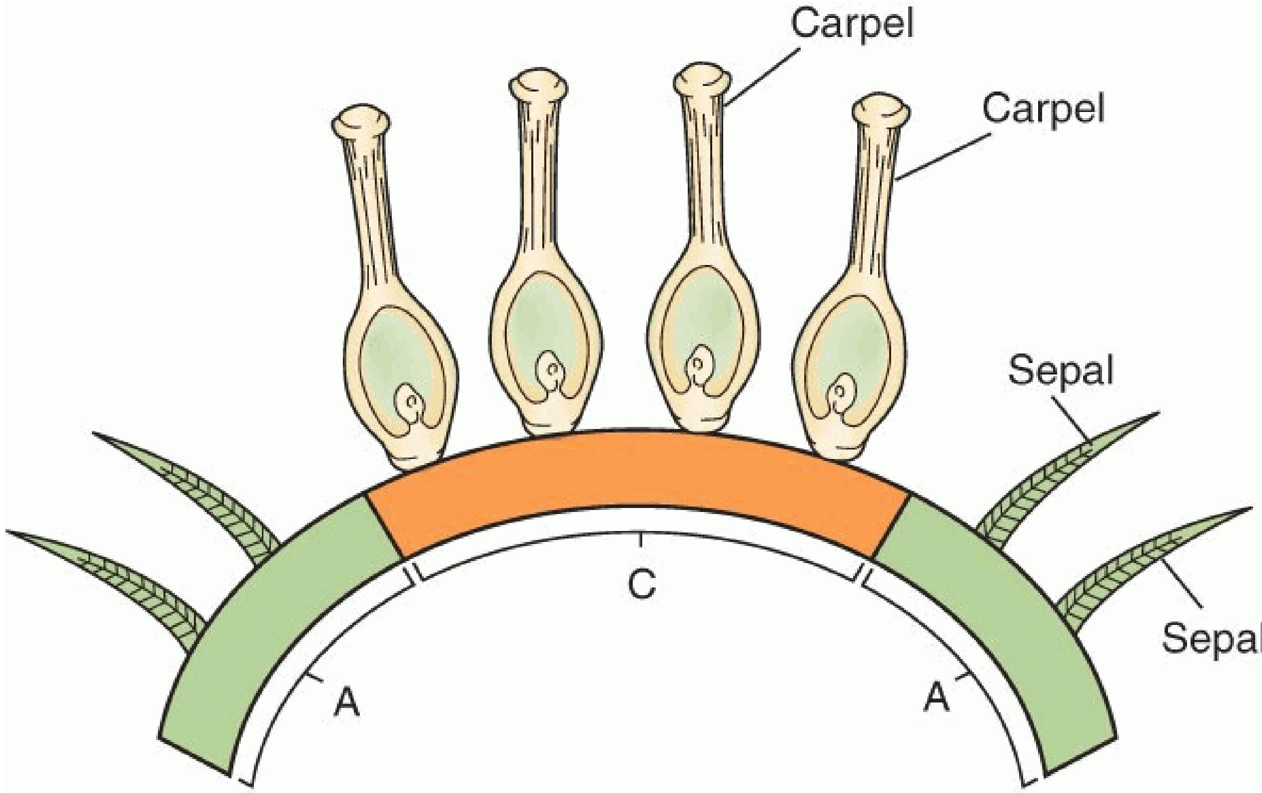


49.8 Flower development: ABC model

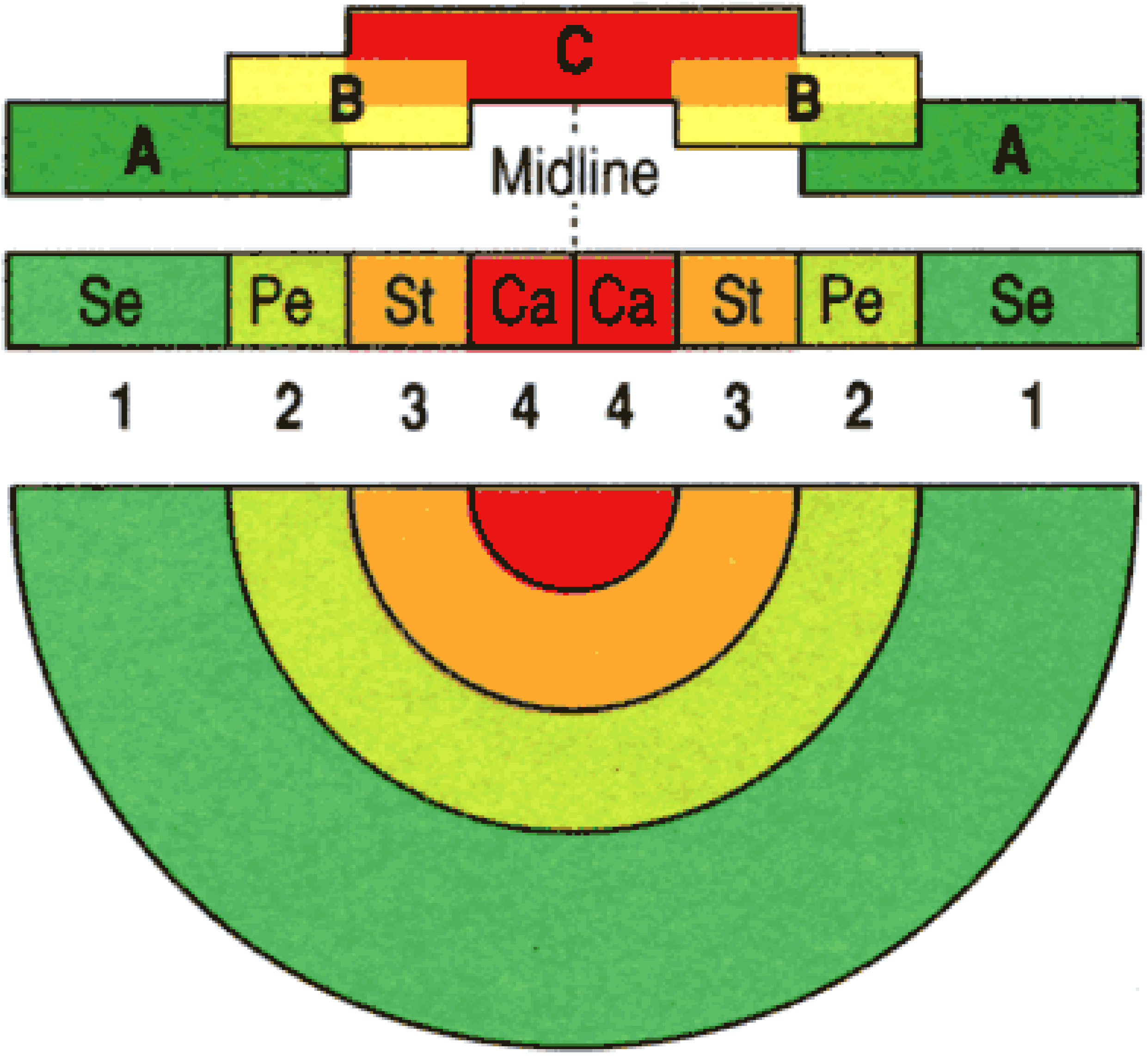
ABC-genes

- There are 3 classes of genes expressed in overlapping, concentric rings.
- The A class (like *apetala2* gene) is expressed in the outermost ring and C (like *agamous*) is expressed in the center; B (e.g., *apetala3*) is expressed at the boundary of A and C:
  - A alone → calyx
  - A + B → corolla
  - C + B → androecium
  - C alone → gynoecium

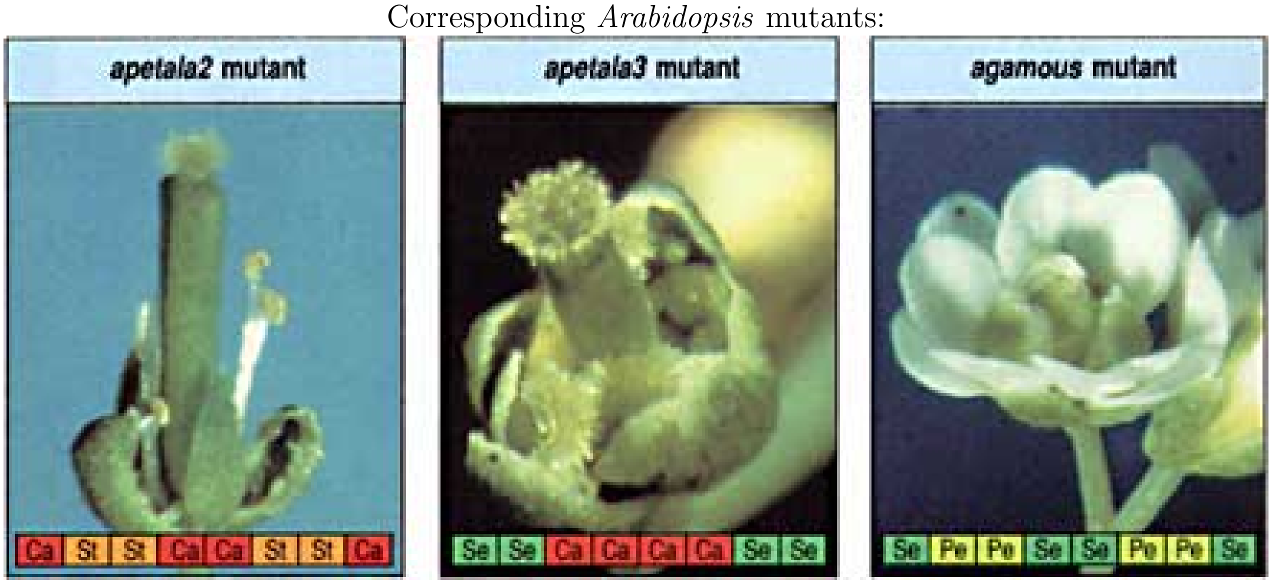
A and C genes "make" sepals and pistils



B genes "transform" them into petals and stamens



Corresponding *Arabidopsis* mutants:

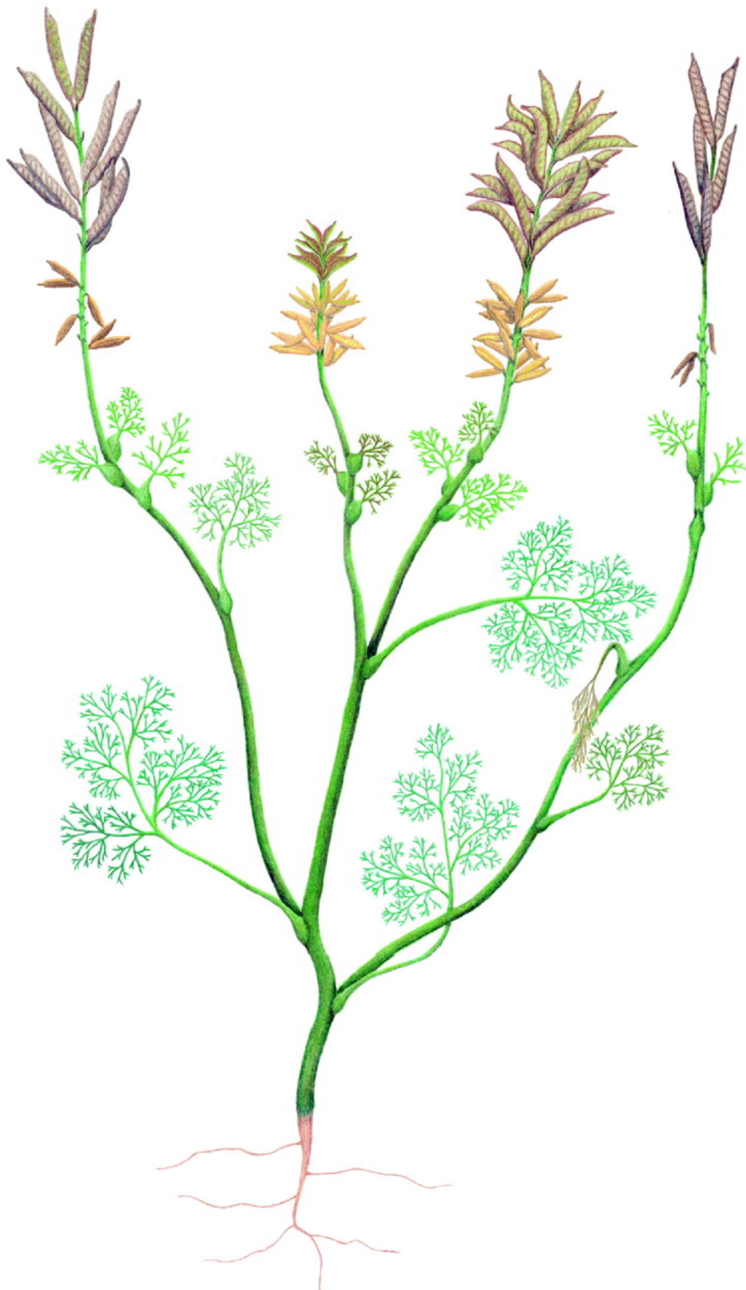


49.9 Primitive flowers

Archaefructus

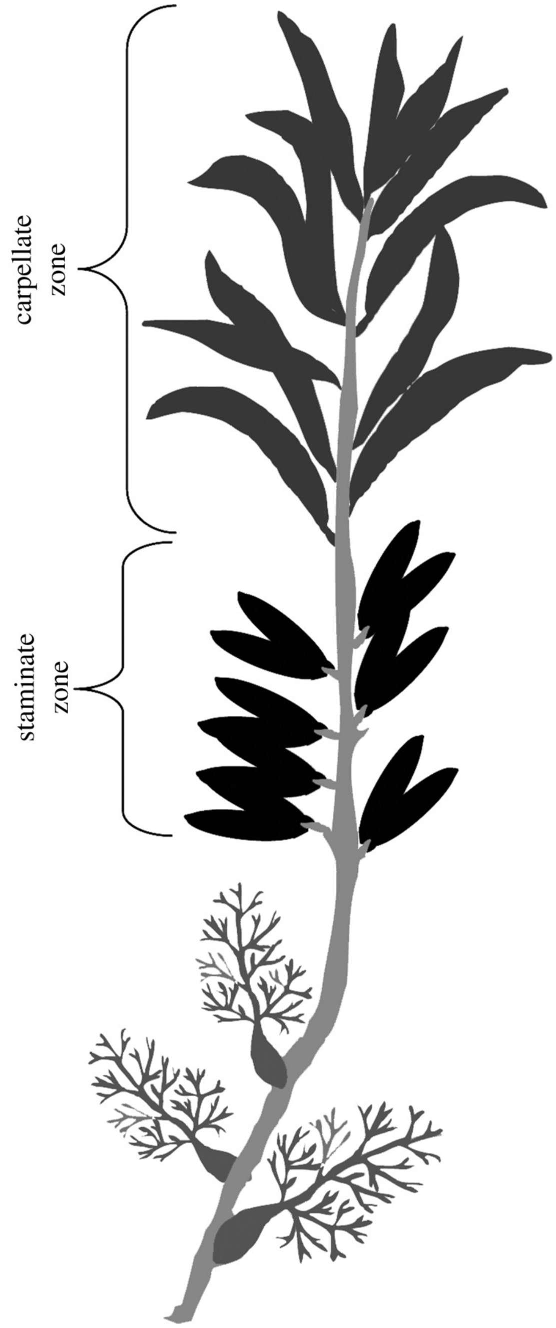
- Fossil water plant from lower Cretaceous of China
- Very primitive fructifications which are not yet compacted in flower
- Multiple free carpels, paired stamens

Archaefructus reconstruction



Archaefructus reconstruction, 3D

***Archaefructus*, scheme of "flower"**



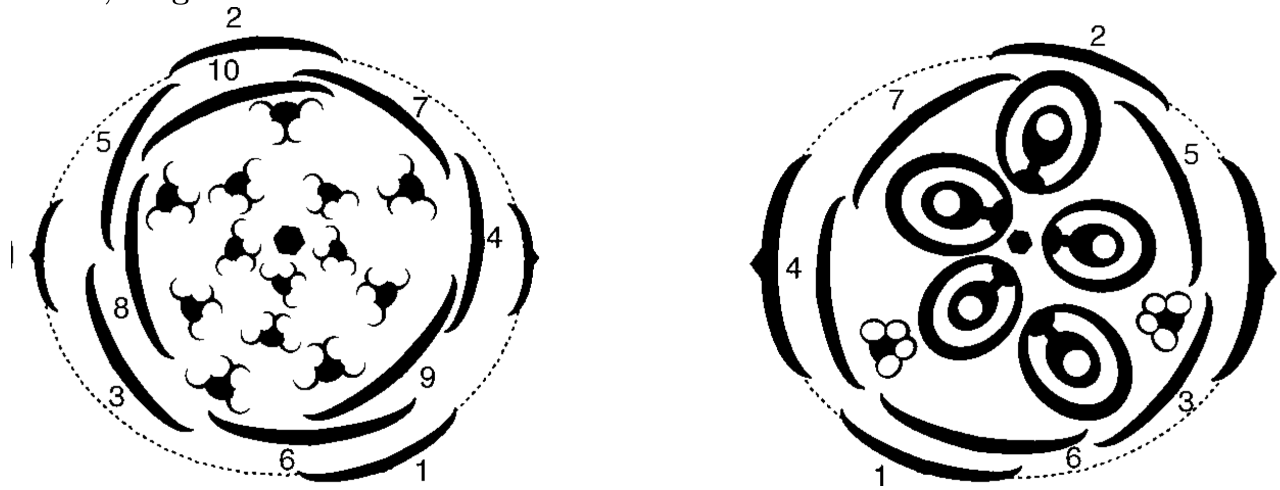
Amborella

- Small forest shrub of New Caledonia (big island in Pacific ocean)
- Have irregular flowers, stylar canal, unusual embryo sac (5 cells)

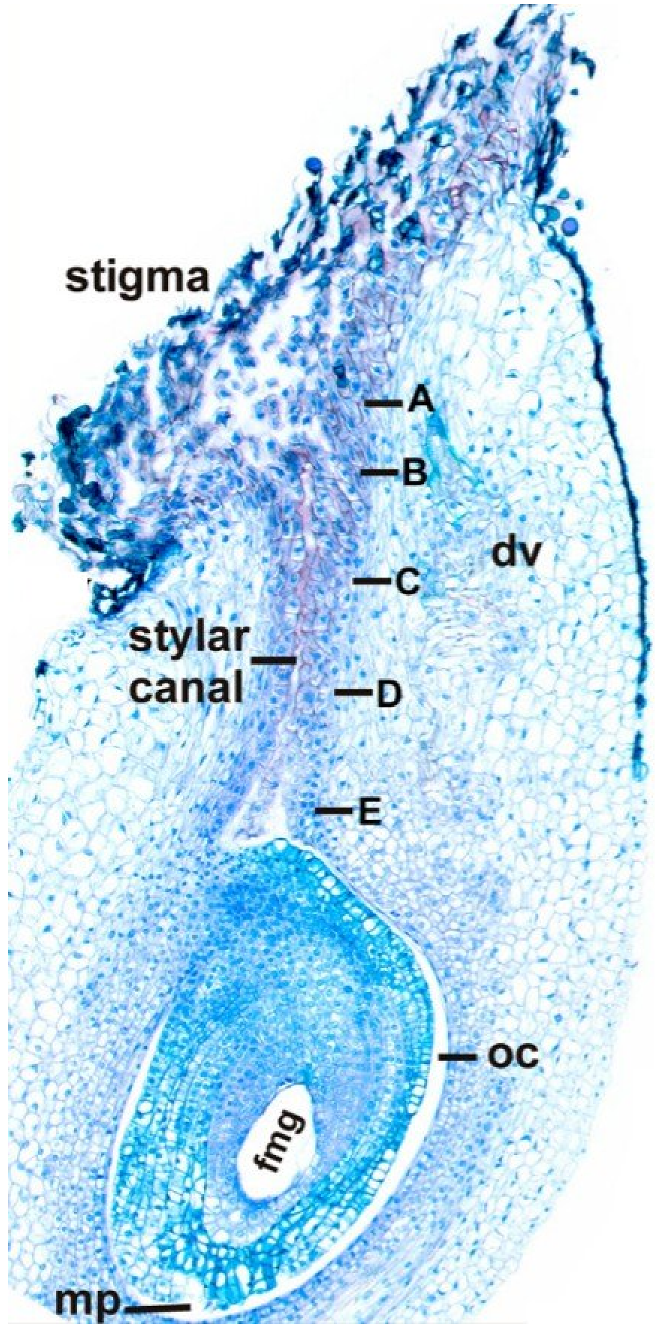
***Amborella*, branch with male flowers**

Amborella, male and female flowers

***Amborella*, diagrams of male and female flowers**

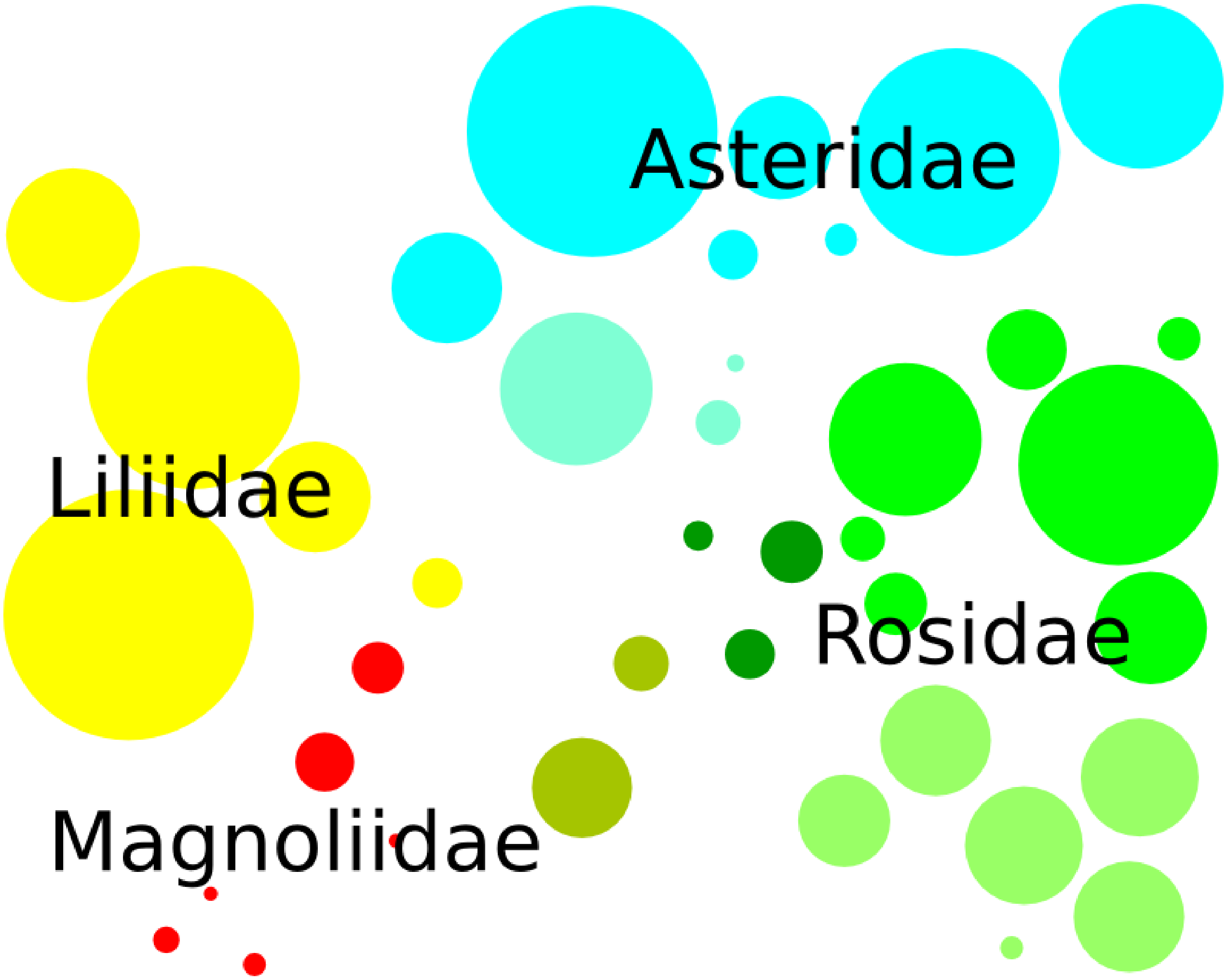


***Amborella* stylar canal**

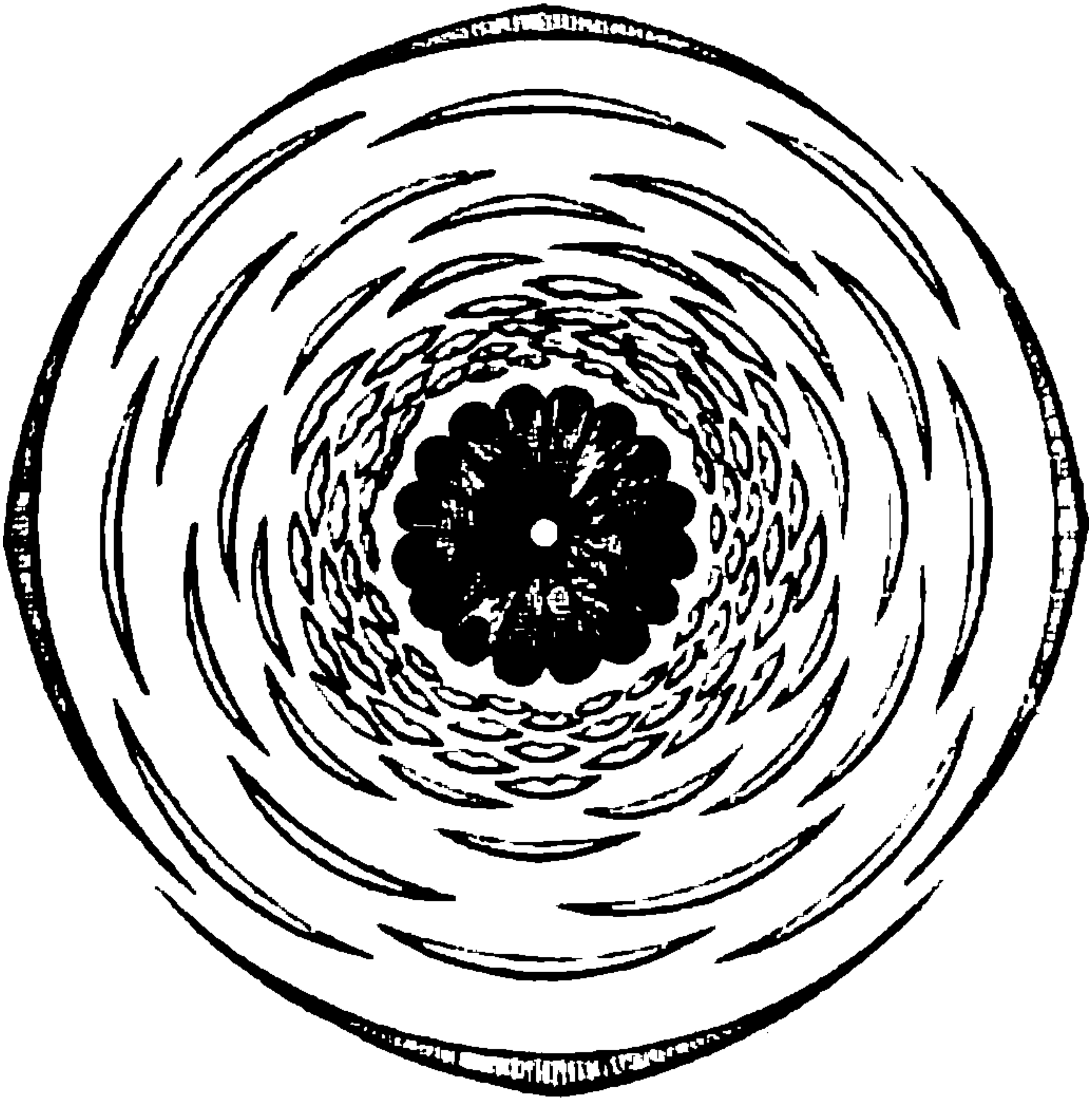


49.10 Four subclasses of angiosperms

Angiosperms: subclasses and orders

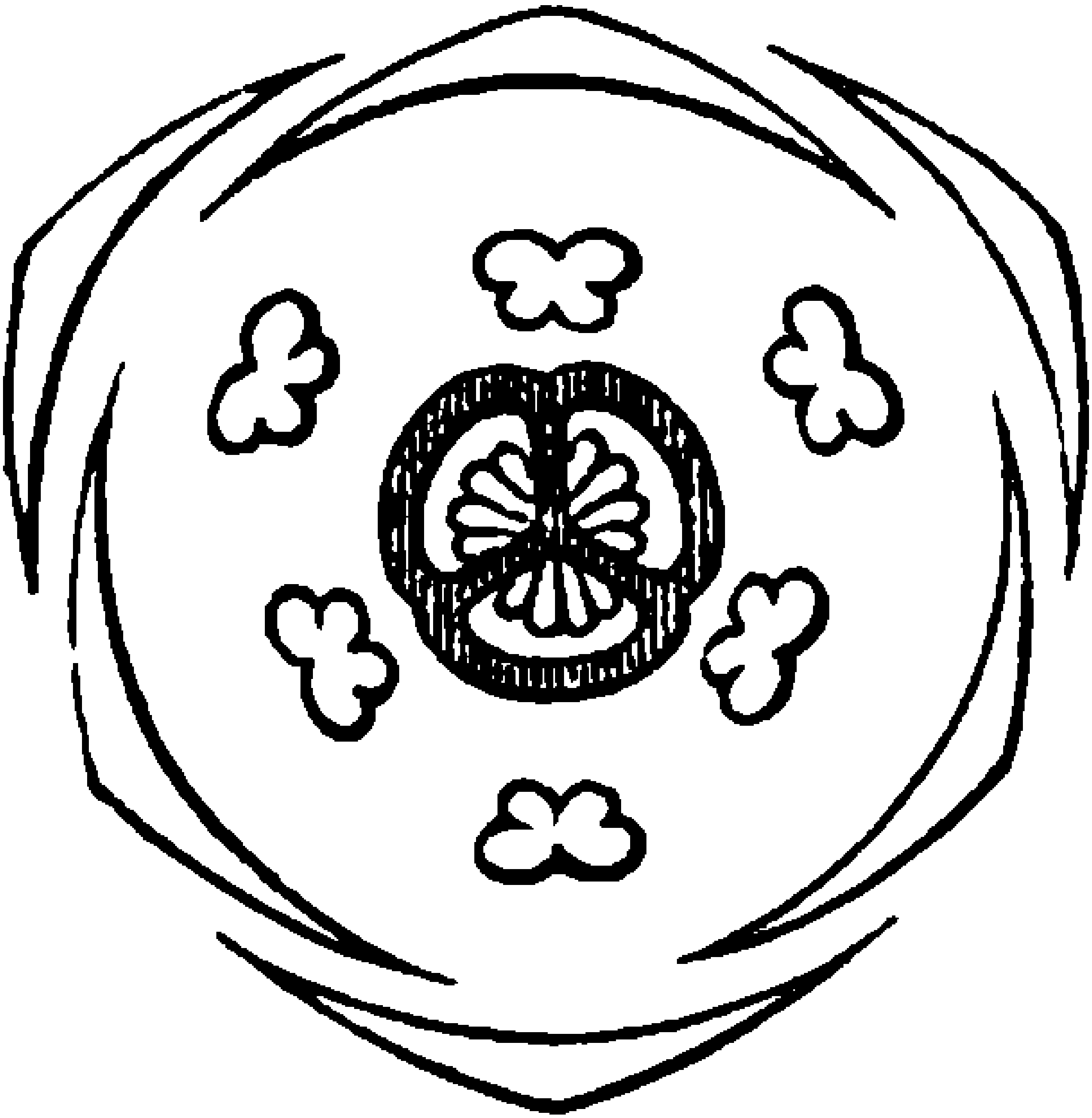


Magnoliidae portrait



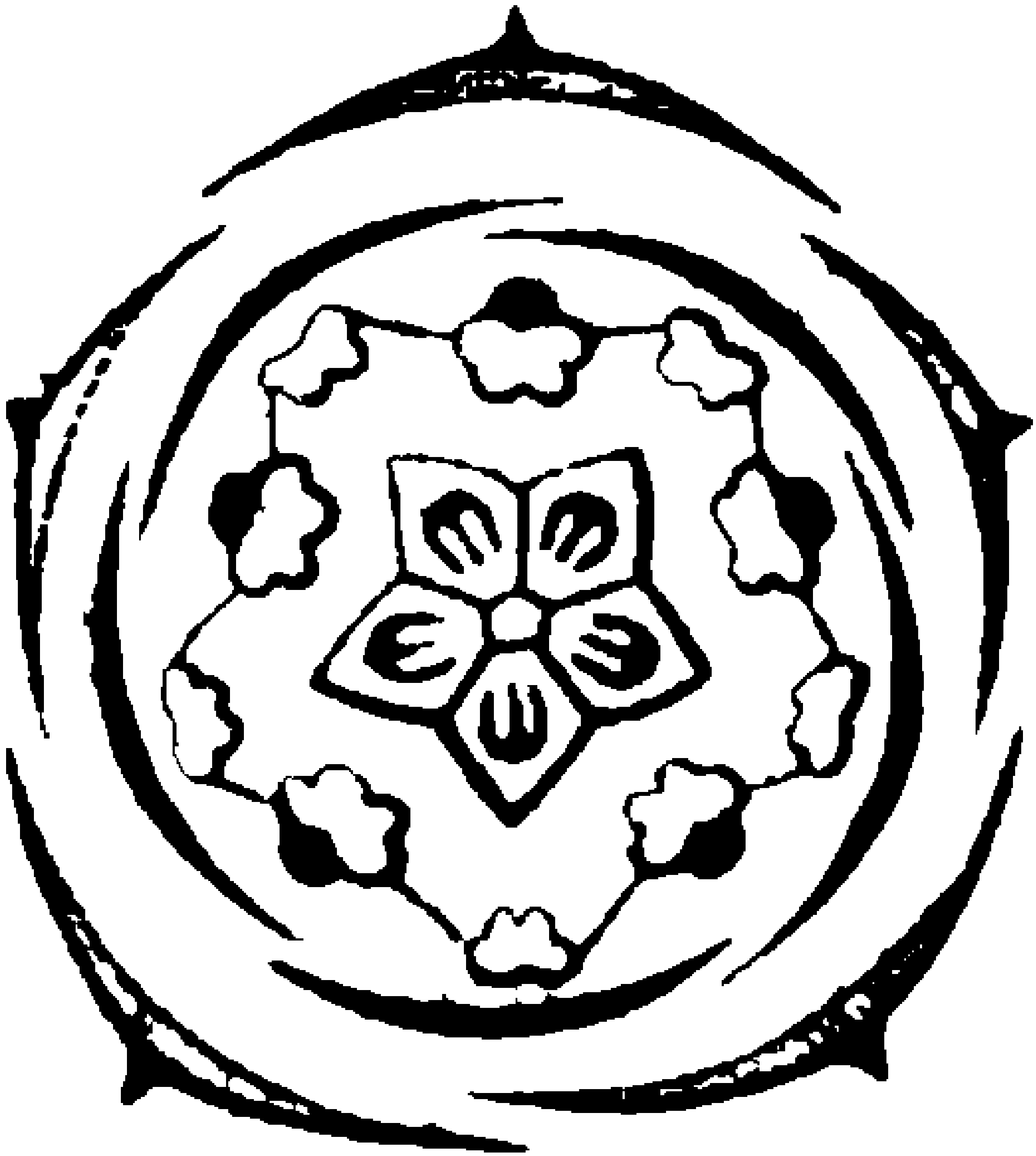
Nymphaea sp. (water-lily): multiple, disorganised

Liliidae portrait



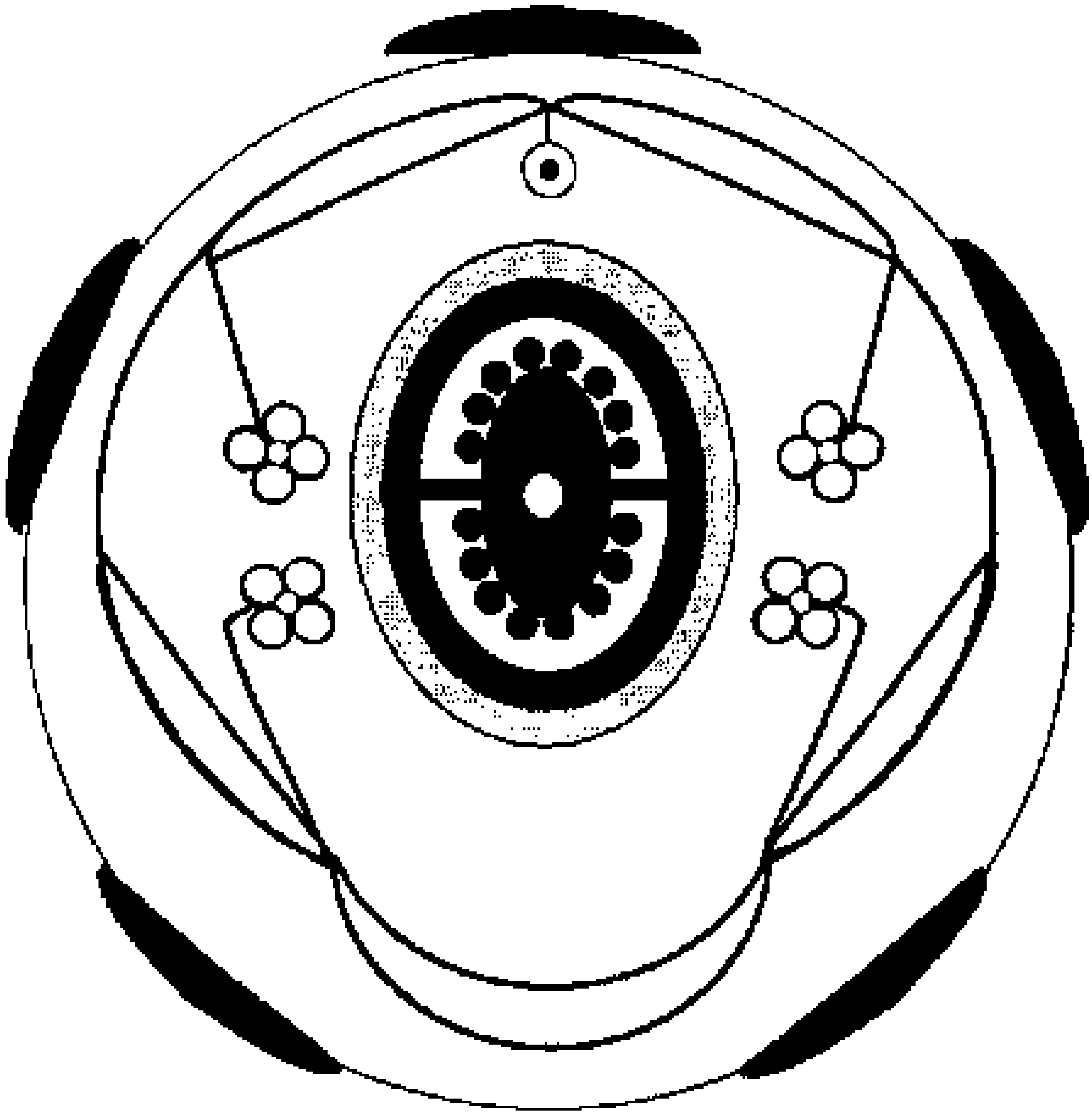
Acorus calamus (calamus, or sweet flag): trimerous

Rosidae portrait



Geranium sp.: pentamerous or tetramerous, petals free

Asteridae portrait



Penstemon sp. (beard-tongue): petals fused, more petals than carpels

49.11 Pollination

How to avoid pollination: apomixis

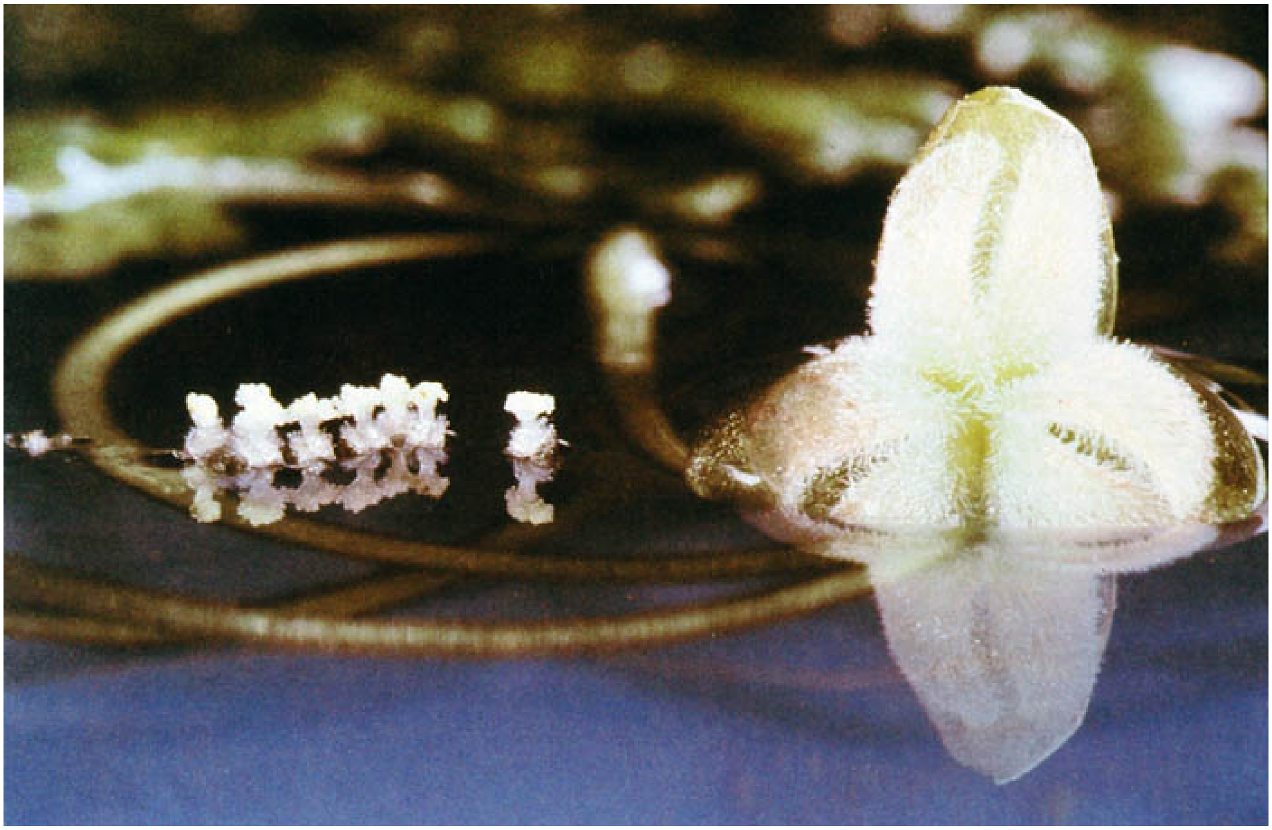
- Apomixis is a reproduction with reproductive organs but without fertilization
- **Apospory**: embryo develops from maternal diploid tissue, without meiosis; here asexual reproduction becomes vegetative
- **Apogamy** (i.e., parthenogenesis): embryo develops from unfertilized gamete after diploidization; sexual reproduction becomes vegetative

Pollination

- Self-pollination (only slightly better that apogamy)
- Cross-pollination: abiotic (gravity, wind, water) and biotic (insects, birds, bats, sometimes even possums)
- Every pollination type has associated **pollination syndrome**

Wind pollination: hazelnut

Water pollination: vallisneria



Bat pollination: cacti

Possum pollinaiton: Australian Myrtaceae

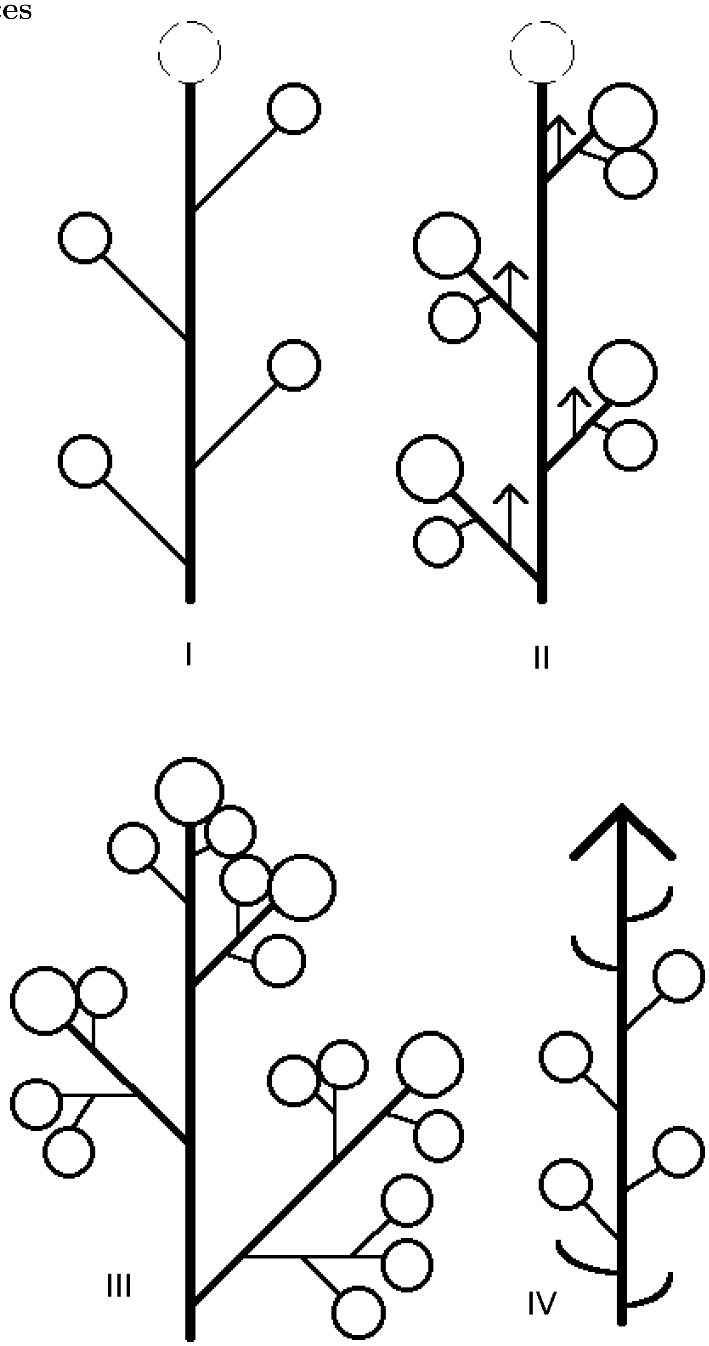
49.12 Inflorescences

Types of inflorescences

Inflorescence is an isolated generative shoot bearing flowers

- Model I. Raceme and its derivates
  - Simple: raceme (developed man axis, developed lateral axes: 11), spike/catkin (developed main axes, reduced lateral axes: 10), umbel (01), head (00)
  - Compound: compound raceme (11/11), compound umbel (01/01) etc.
- Model II. Thyrsus and its derivates
  - Reduced (cymes): dichasium, cincinnus (scorpioid inflorescence) etc.
  - Thyrses in a strict sense
- Model III. Closed panicle (also umbel-like panicles)
- Model IV. Intercalary inflorescences

Models of inflorescences



49.13 Seeds

Definition

- "Mature ovule"
- Chimeric organ consists of seed coat, endosperm and embryo

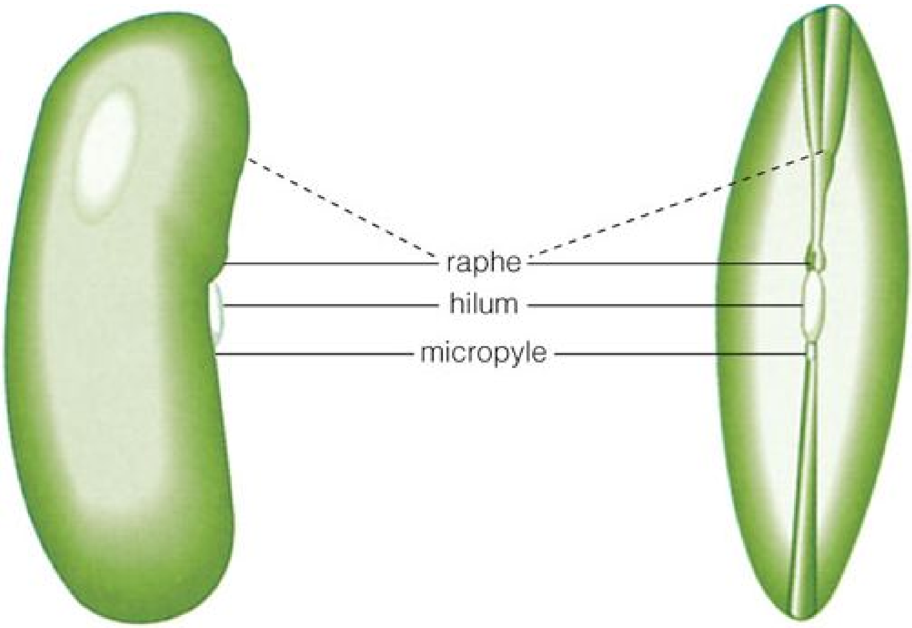
Origin of seed layers

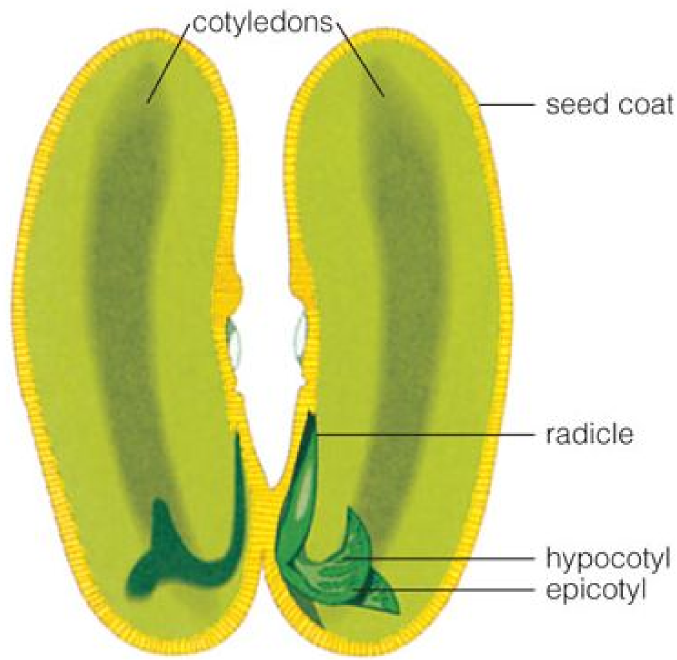
Layer	Ploidy	Origin
Seed coat	$2n$	Integument of ovule
Endosperm_2	$3n$, sometimes $2n$	Fertilized central cell of embryo sac
Embryo	$2n$	Fertilized egg
Endosperm_1	n	Female gametophyte (gymnosperms!)
Perisperm	$2n$	Nucellus of ovule

Seed structure variations

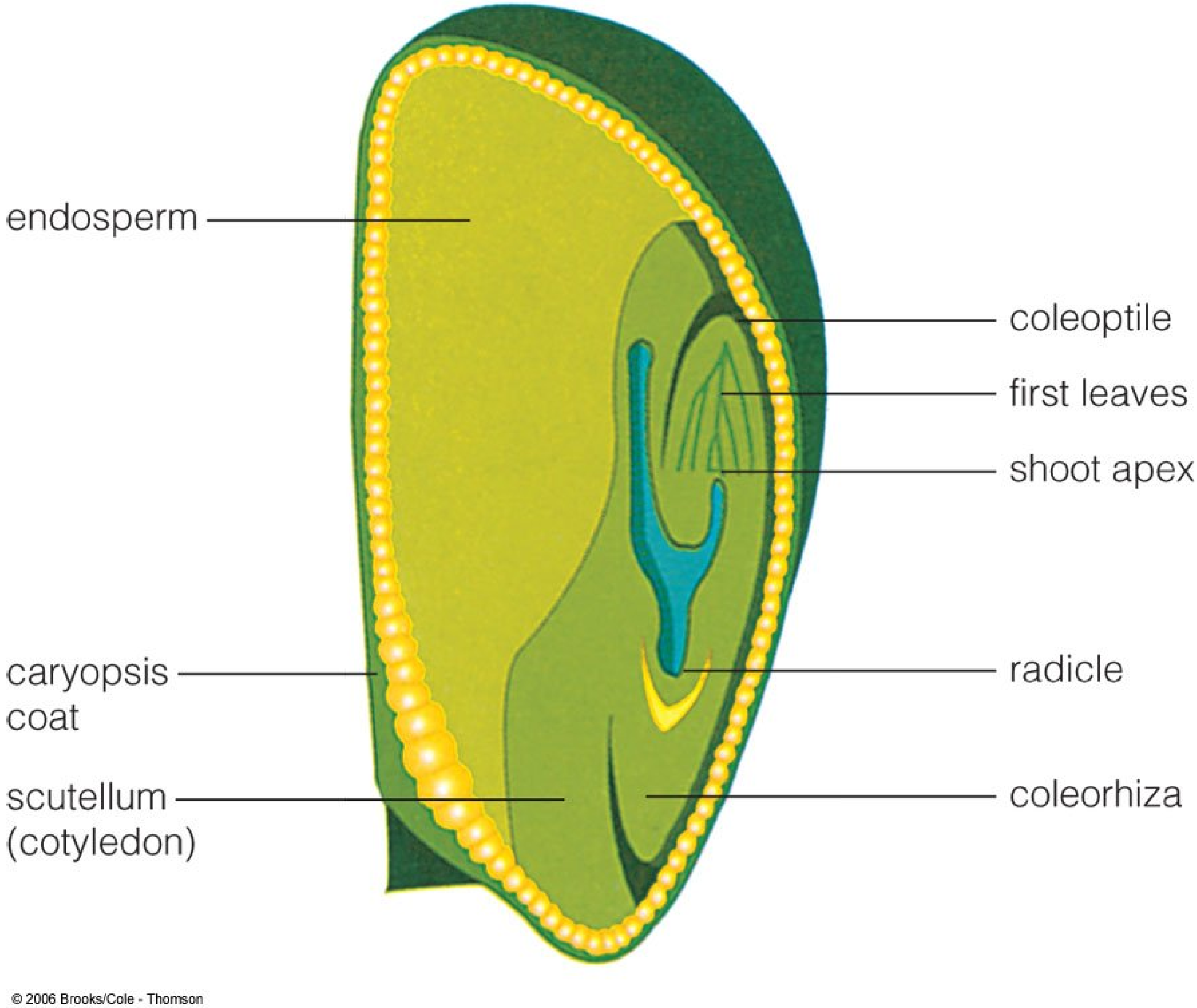
- Seed with endosperm (onion): cotyledon(s): embryonic leaves, radicle: embryonic root, apex: embryonic bud
- Seed without endosperm (beans and other Leguminosae): cotyledons, radicle, hilum, raphe
- Grass (Gramineae) seeds: coleoptile, coleorhiza, scutellum

Bean seed


raphe
hilum
micropyle


cotyledons
seed coat
radicle
hypocotyl
epicotyl

Grass seeds



Cotyledons

- Monocots have lateral bud and terminal primary leaf (cotyledon)
- Other seed plants have terminal bud and multiple (2 to many) primary leaves (cotyledons)

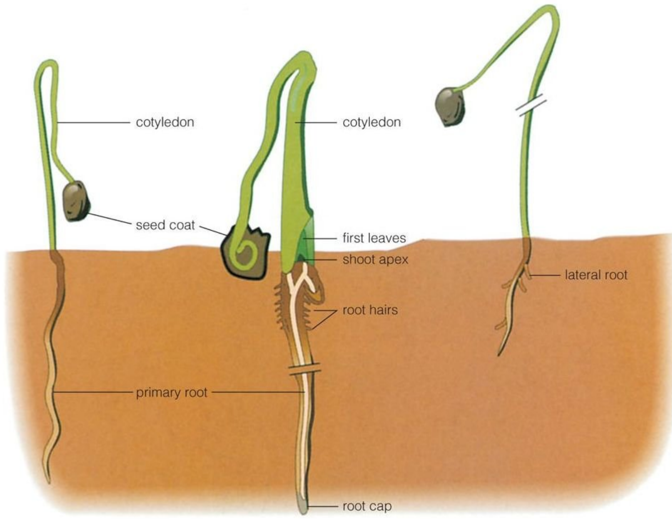
***Pinus* sp.: multiple cotyledons**

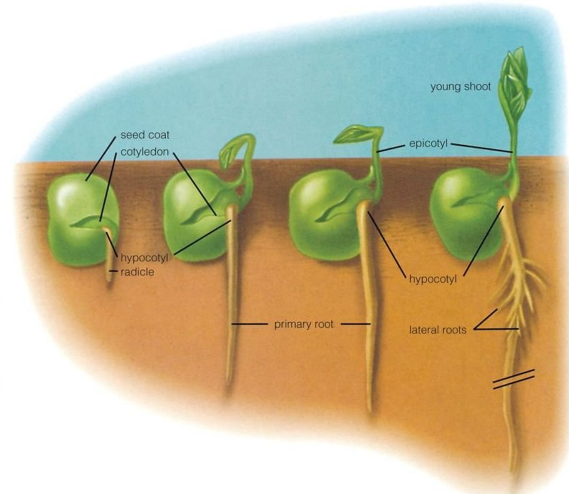
Germination

- Epigeal (e.g., onion, pea). They expose cotyledons and both hypo- and epicotyl.
- Hypogeal (e.g., bean, grasses, palms). They expose only epicotyl (first internode), cotyledons and hypocotyl (root/stem transition) is underground.

Both variants have advantages and disadvantages.

Epigeal *versus* hypogeal germination





49.14 Fruits

Definition and origin

- **Fruit** is a ripened ovary, flower or inflorescence
- Fruit coat and pericarp (exocarp + mesocarp + endocarp) origin mostly from pistil wall

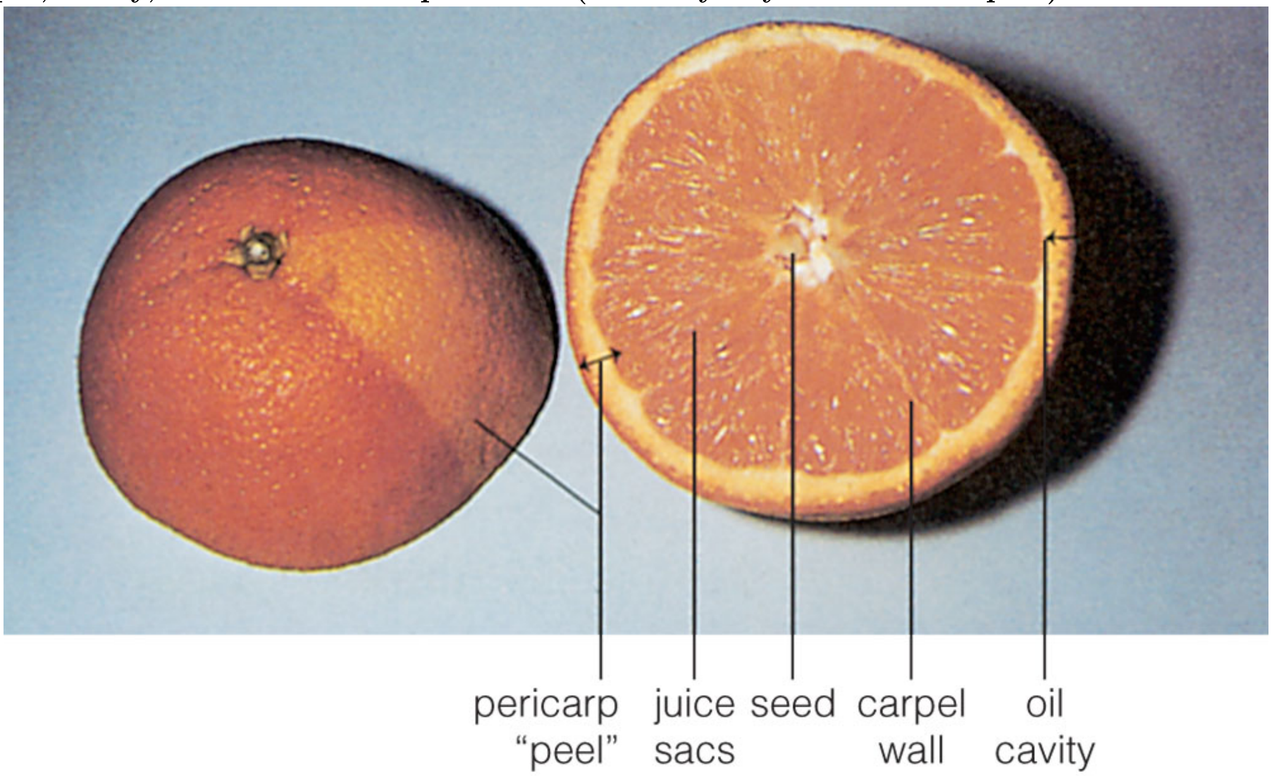
Trivial classification: criteria

- **Simple**, **multiple** (aggregate) or **compound**. Simple fruits are from one pistil (cherry), multiple from many pistils of one flower (raspberry), compound—from multiple flowers (pineapple).
- **Dry** or **fleshy**. Fleshy fruits are adapted to animal dispersion through their digestive tract.
- **Dehiscent**, **indehiscent** or **schizocarpic**. Dehiscent (opening) fruit will delegate dispersal function to individual seeds; indehiscent (closed) fruit will take these functions but will require less seeds per fruit to avoid competition between seedlings. Schizocarp has multiple seeds but will be fragmented to many one-seeded parts.

Trivial classification: examples

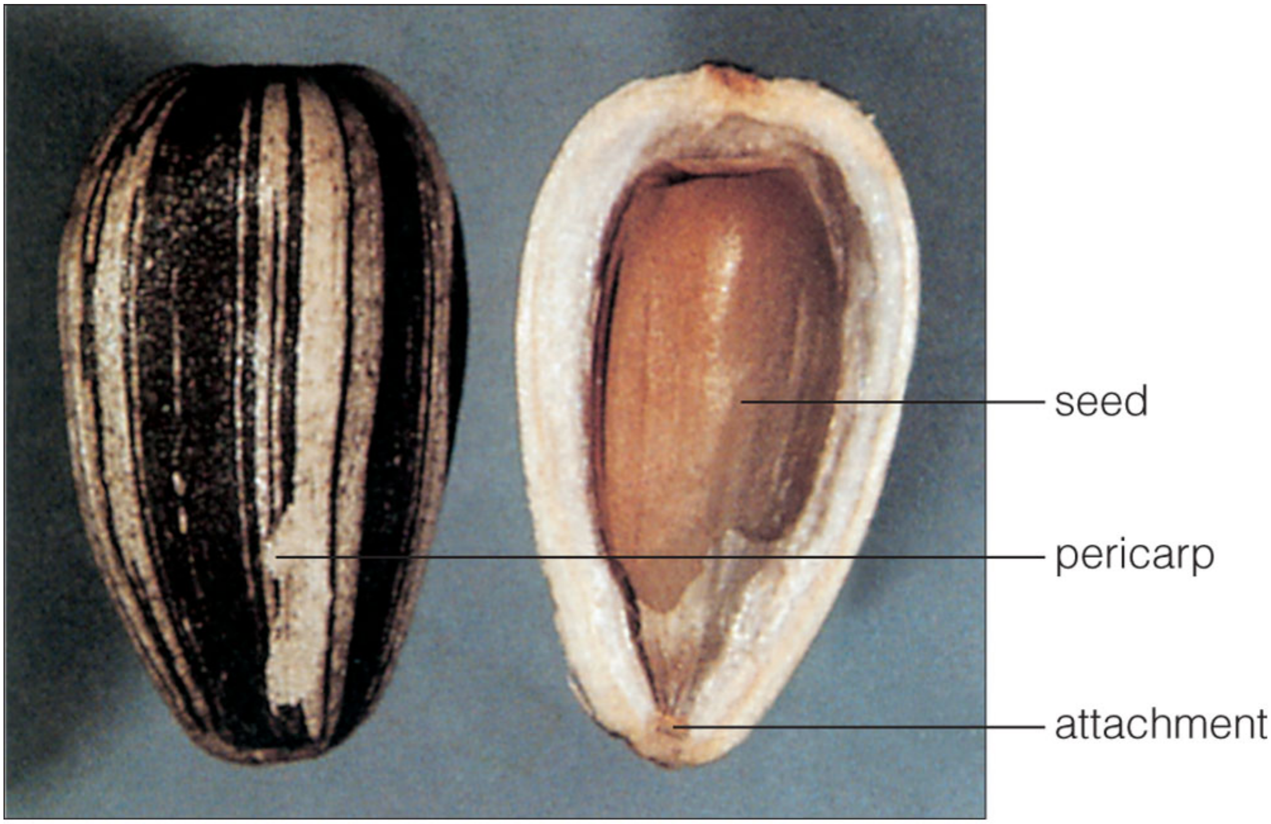
Type	Consistency	Opening	Example
Simple	Fleshy	Indehiscent	Drupe (one seed), Berry (multiple seeds), Hesperidium (citruses), Pome (apple, pear: from inferior ovary)
Simple	Dry	Dehiscent	Legume (pod), Capsule, Silique (fruit of cabbage family)
Simple	Dry	Schizocarpic	Regma (spurge), Samara (maple), Shizocarp (umbel family)
Simple	Dry	Indehiscent	Caryopsis (grain, fruit of grasses), Nut (incl. acorn), Achene (fruit of aster family)
Multiple	Fleshy	Indehiscent	Multiple drupe (raspberry)
Multiple	Dry	Dehiscent	Follicle (many pods together)
Multiple	[Dry]	Indehiscent	Multiple nut (strawberry)
Compound	Fleshy	Indehiscent	Compound berry (pineapple)
Compound	[Dry]	Indehiscent	Compound nut (fig)

Simple, fleshy, indehiscent: hesperidium (or berry if you like it simpler) of *Citrus*

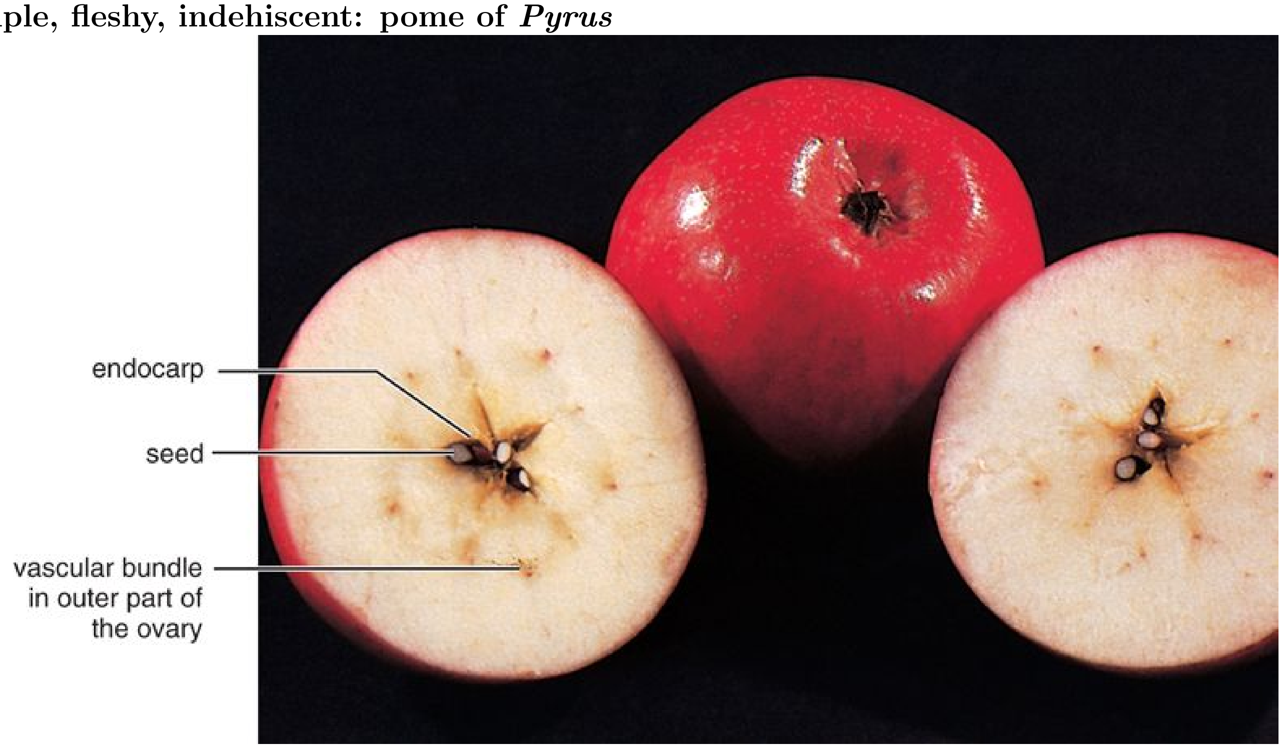


Simple, dry, dehiscent: pod of *Erythrina* legume

Simple, dry, indehiscent: achene (not "seed"!!!) of *Helianthus*



Simple, fleshy, indehiscent: pome of *Pyrus*



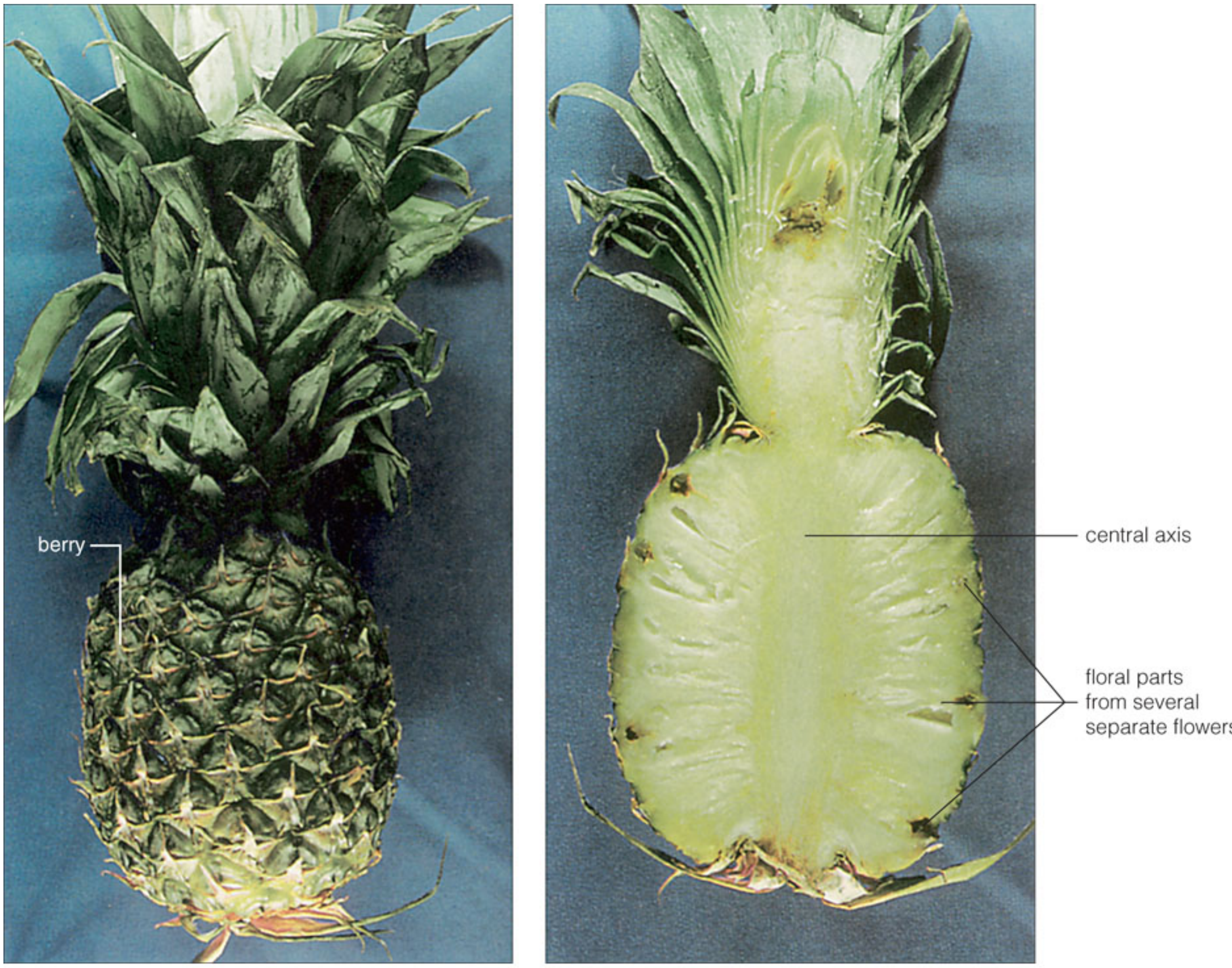
Samara of *Acer*

Schizocarp of *Zizia*

Multiple nut of *Fragaria* sp. (strawberry)

Multiple drupe of *Rubus* sp. (raspberry)

Compound berry of *Ananas comosus* (pineapple)



Compound fruit of *Ficus carica* (fig tree)

Short anonymous absolutely voluntary survey

A. What do you **like** most in Biology 154?

B. What do you **dislike** most in Biology 154?

C. **Which lab** do you remember most of all?

D. Please grade (1—bad, 5—excellent):

   (a) Lectures
   (b) Labs
   (c) Final questions
   (d) Exams

E. How to improve the textbook?

Summary

- **Flower** is a compact three-zoned generative shoot
- Three main zones of flower: sterile (**perianth**), male (**androecium**) and female (**gynoecium**)

- **ABC-genes** determine the fate of cells which are forming flower
- **Inflorescence** is an isolated generative shoot bearing flowers
- **Seed** is a chimeric organ consists of seed coat, endosperm and embryo
- **Fruit** is a ripened ovary, flower or inflorescence
- BOTANY IS COOL!

For Further Reading

References

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