Chlorophyta
- Green Algae -

course: “Anatomy and histology of benthic algae and halophilic plants of the Baltic Sea”

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Part 1: Characteristics of the *Chlorophyta*

Part 2: Taxonomy of the *Chlorophyta*

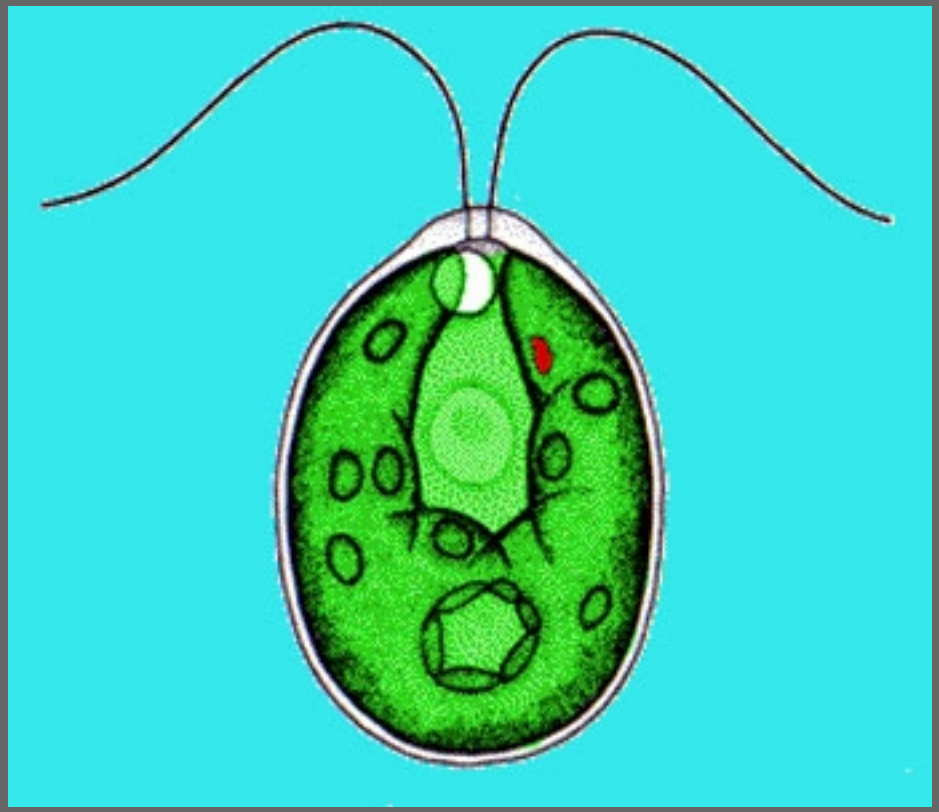
Part 3: Green Algae of the Baltic Sea

Characteristics of the *Chlorophyta*

- **morphological / ultrastructural characteristics**
  - flagella
  - chloroplasts
- **molecular characteristics**
  - pigments
  - reserve compounds

Flagella

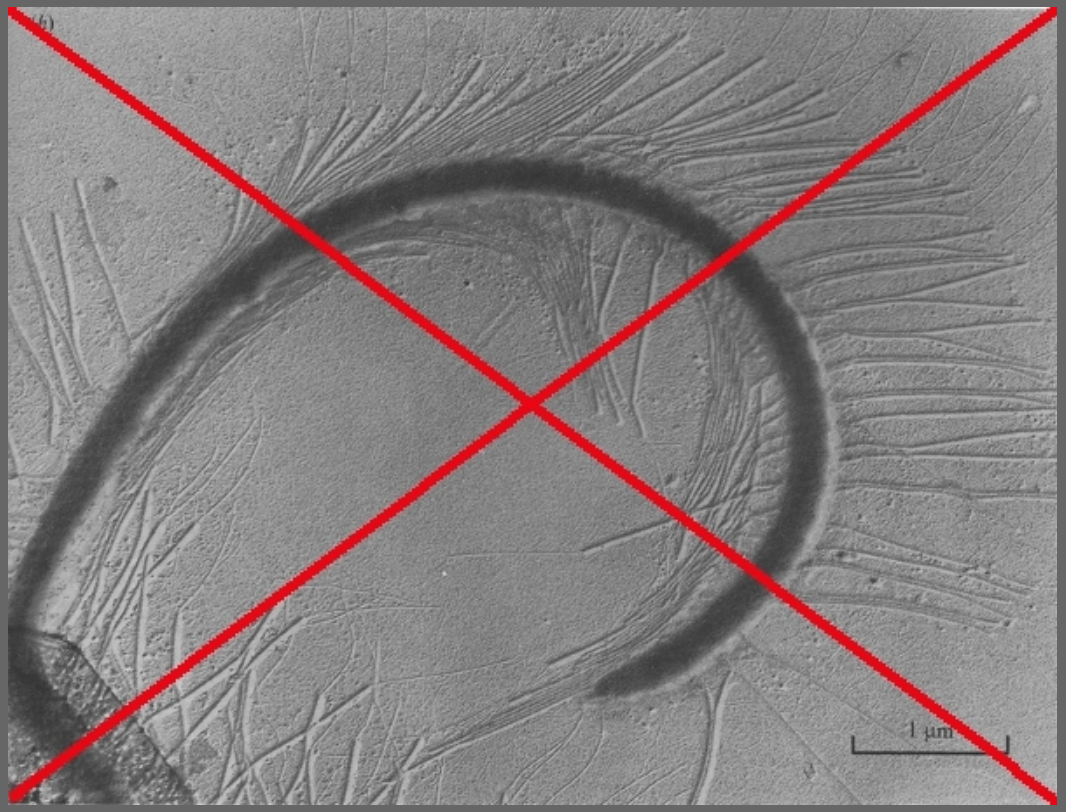
- usually biflagellate, isokont, sometimes 4 or many flagella occur



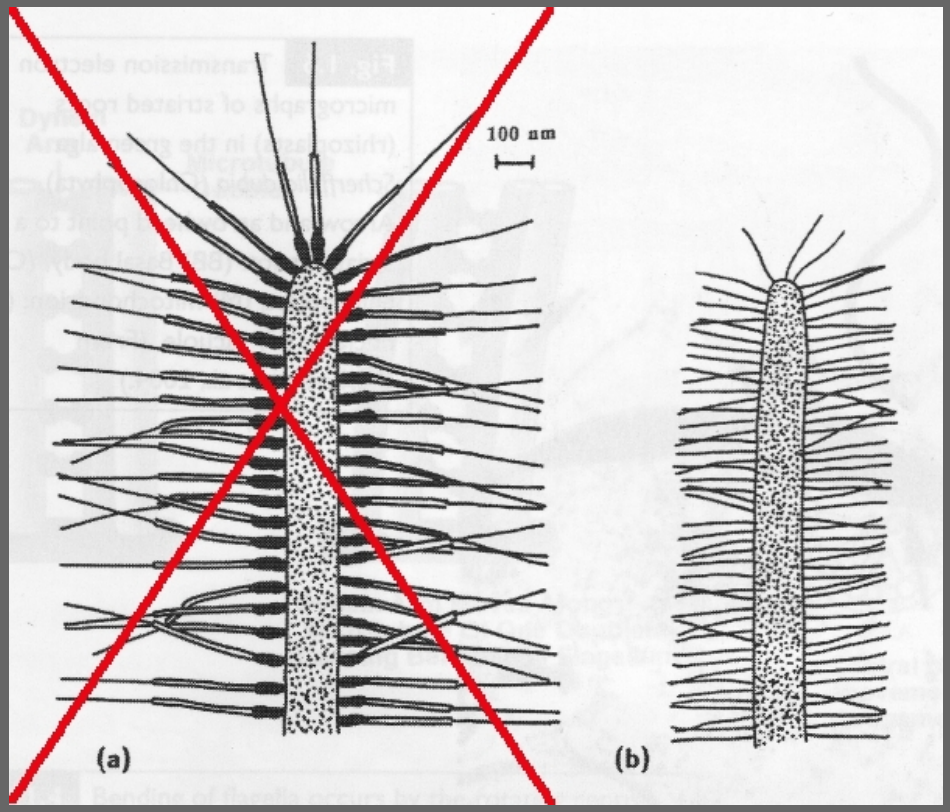
Chlamydomonas sp., drawing [4]

Flagella

- no mastigonemes, but scales and hairy structures not uncommon



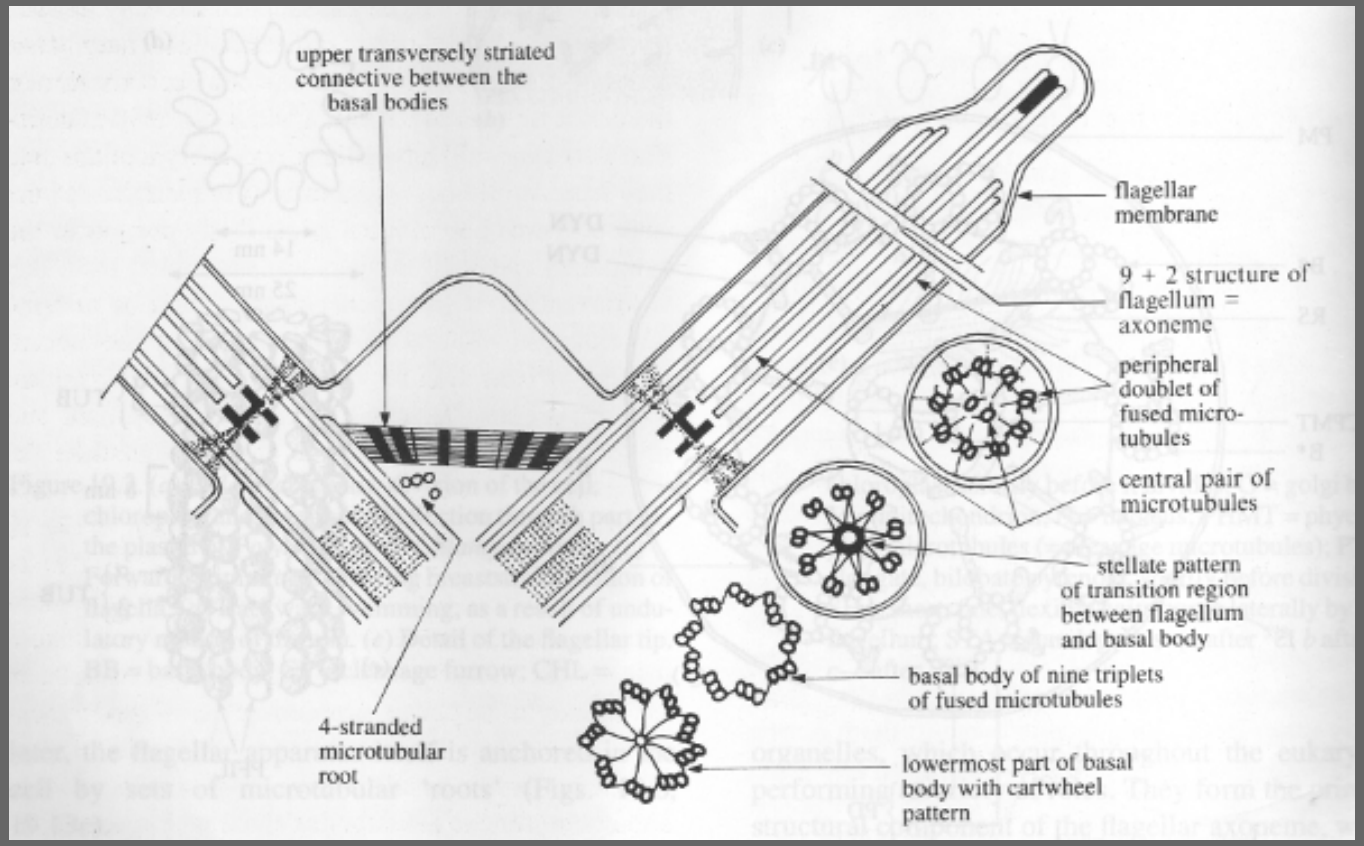
mastigonemes of *Synura*, *Chrysophyceae* [1]



left: tripartite mastigonemes
right: non-tubular hairs [2]

Flagella

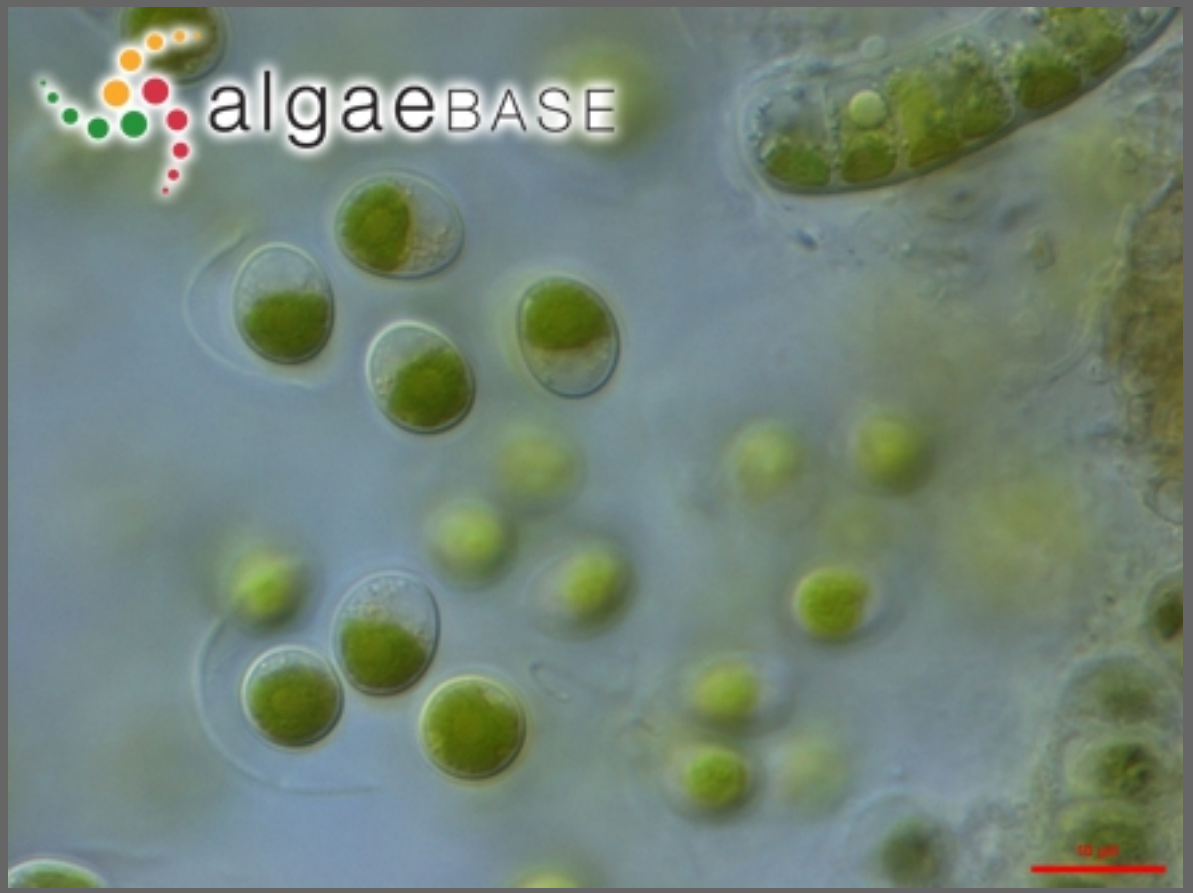
- stellate structure in cross-section of flagellum transition zone



flagellum of *Chlamydomonas reinhardtii*, cross-section [1]

Chloroplast

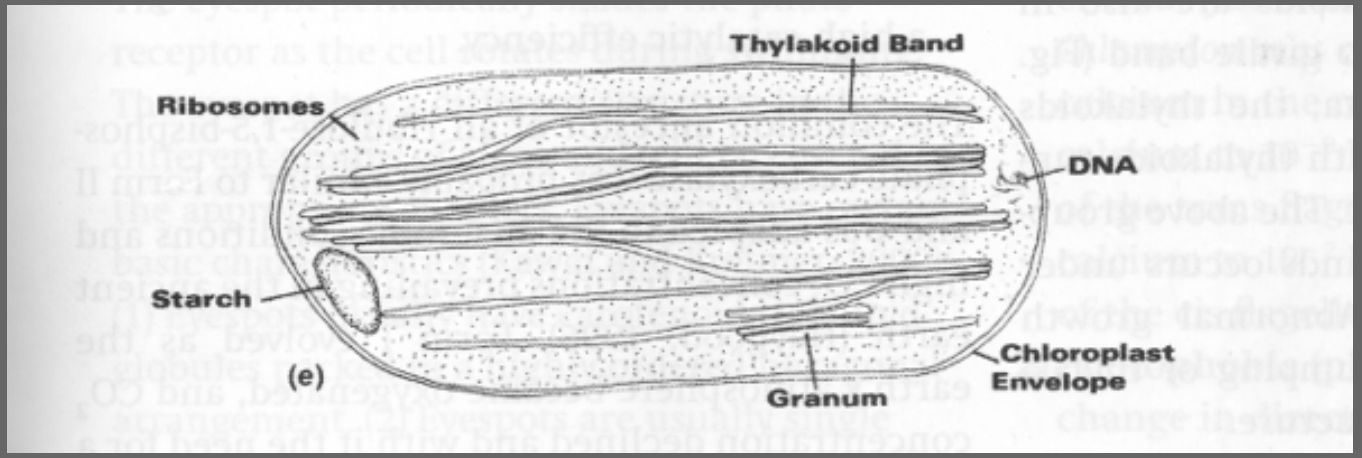
- chloroplasts are green, no masking pigments



Chlorella vulgaris [3]

Chloroplast

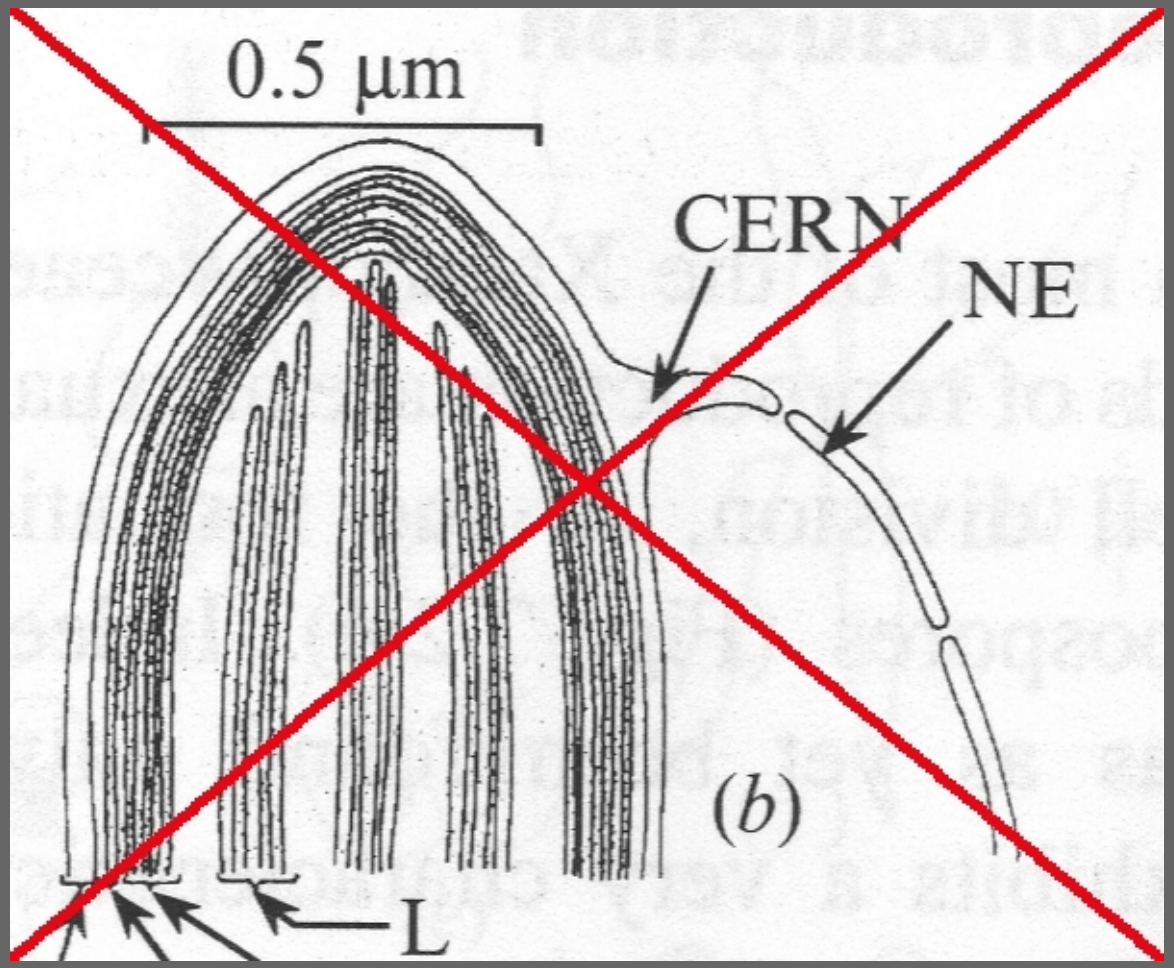
- thylakoids as lamellae, grana or pseudograna stacks of 2 – 6 or more



'chlorophycean' chloroplast [2]

Chloroplast

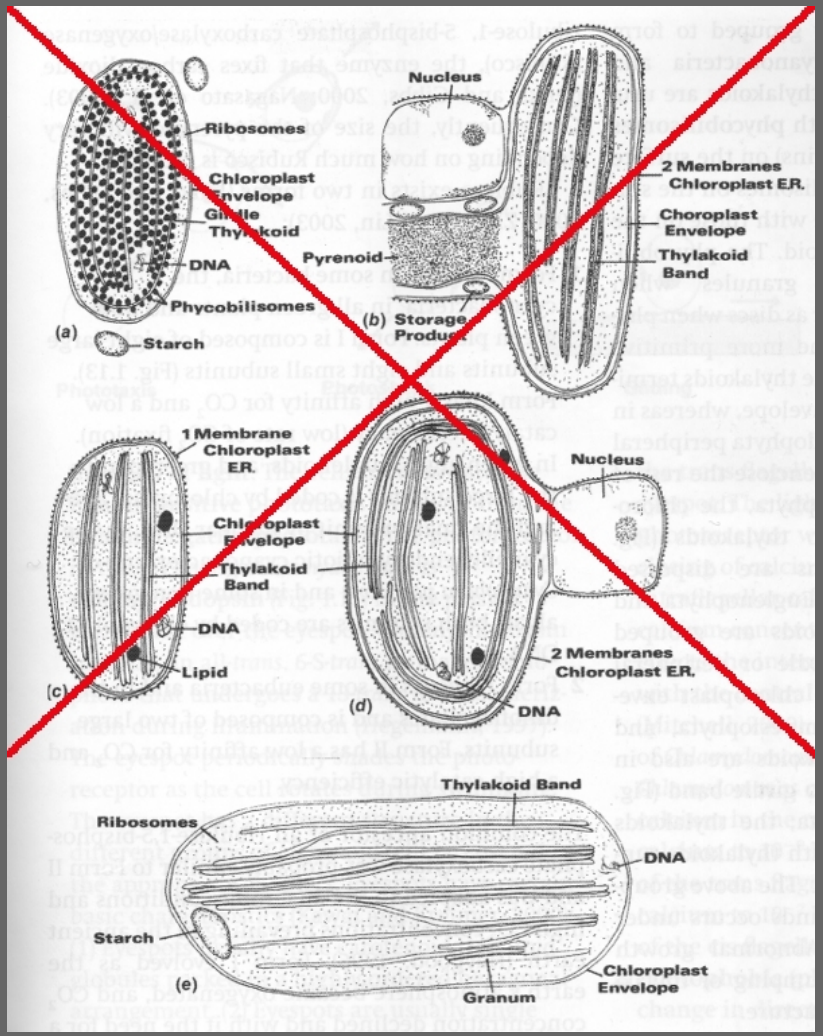
- no girdle lamella



girdle lamella from chloroplast of *Trebonema*, *Xanthophyceae* [1]

Chloroplast

- no ER membrane around chloroplast envelope
- chloroplast derived from primary endosymbiosis with cyanobacterium

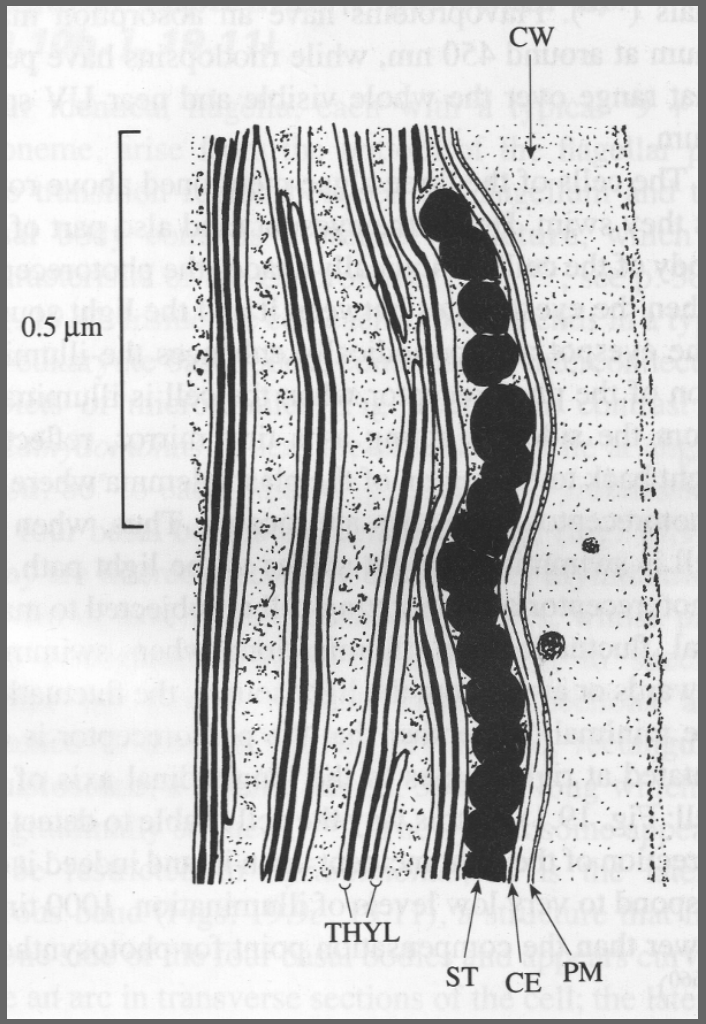


a) *Rhodophyta*
b) *Cryptophyta*
c) *Dinophyta*
d) *Heterokontophyta*
e) *Chlorophyta*

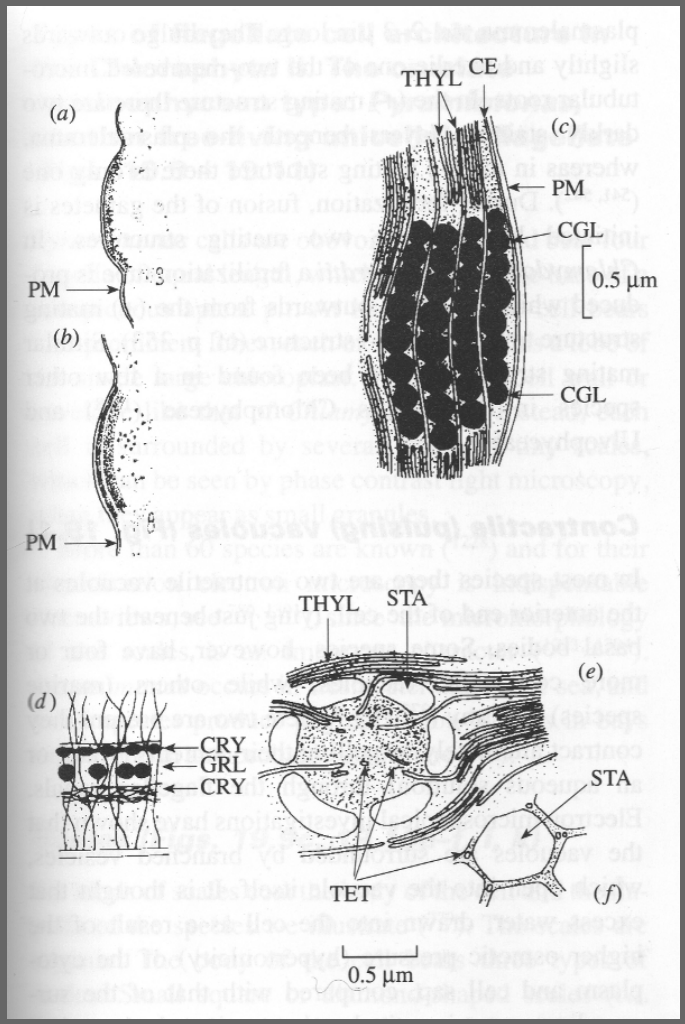
chloroplasts from various algal groups [2]

Chloroplast

- eyespot (stigma) and pyrenoid within chloroplast



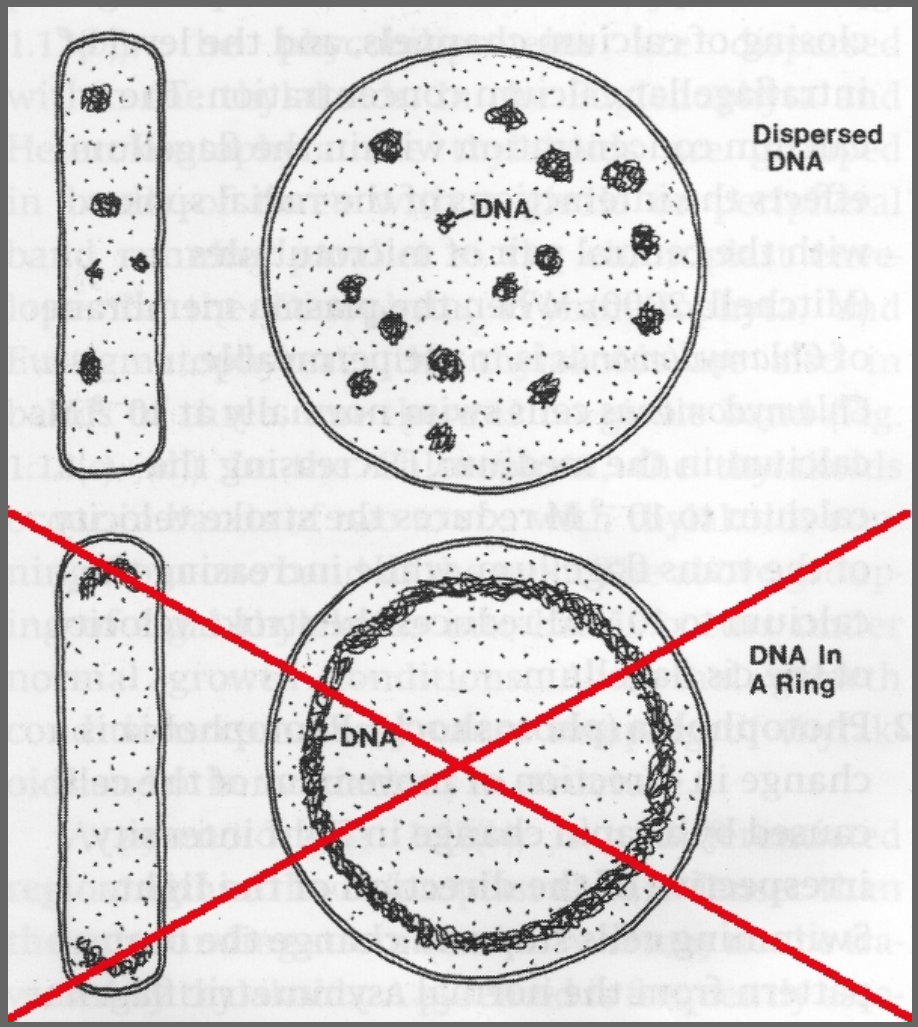
Chlamydomonas eugametos
eyespot [1]



Chlamydomonas reinhardtii
eyespot, pyrenoid [1]

Chloroplast

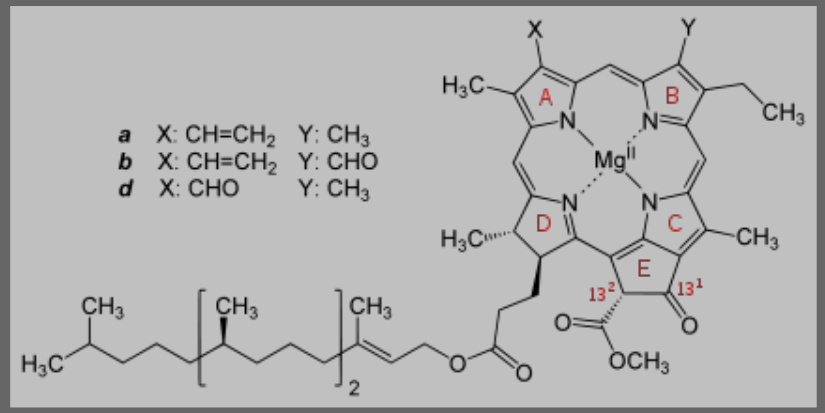
- plastom organized in nucleoids, no ring-shaped circular DNA



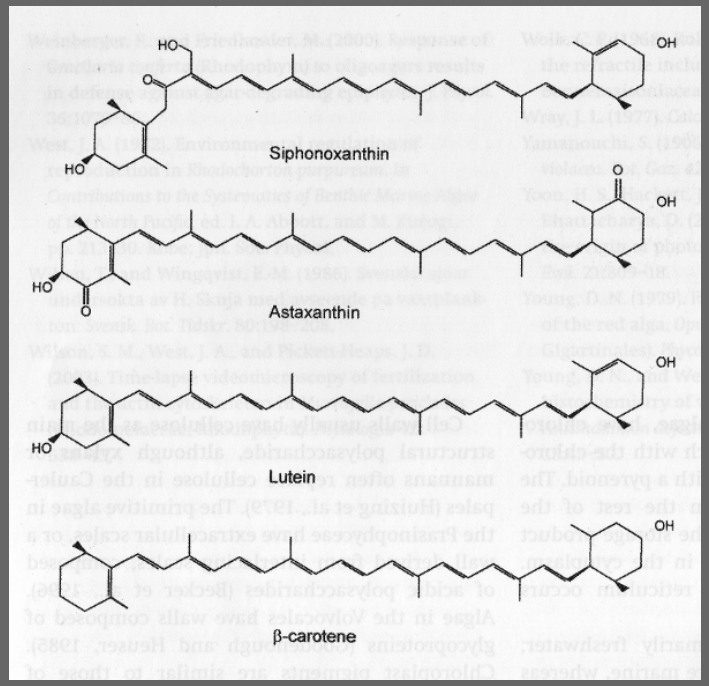
plastid DNA [2]

Pigments

- **chlorophylls**
  - chlorophyll a
  - chlorophyll b
  - (chlorophyll c)
- **xanthophylls**
  - lutein
  - zeaxanthin
  - violaxanthin
  - antheraxanthin
  - neoxanthin
  - siphonoxanthin, siphonein



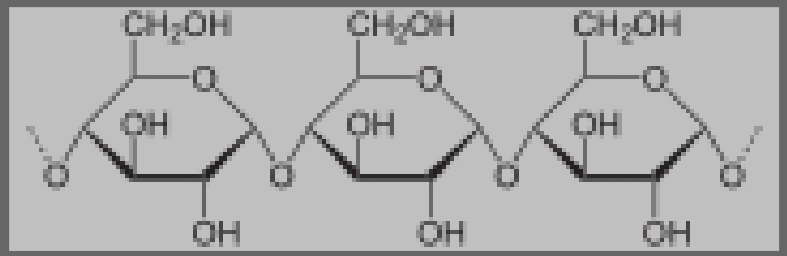
chlorophyll [5]



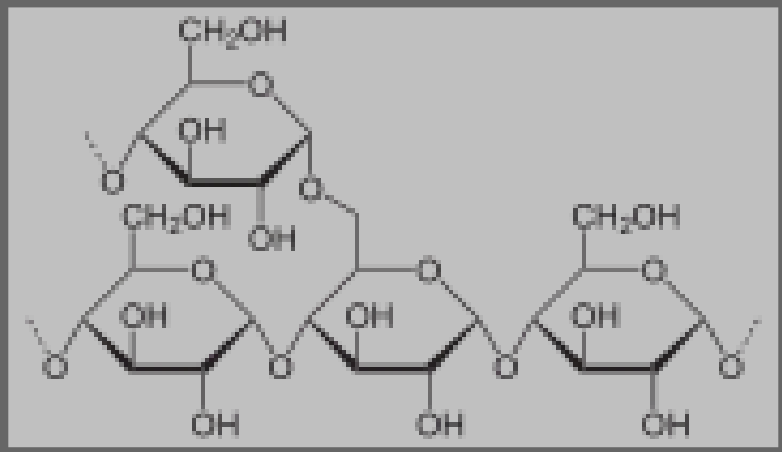
xanthophylls [2]

Reserve compounds

- starch deposited inside chloroplasts (pyrenoids or stroma)



α-1,4-amylose [5]



α-1,4/α-1,6-amylopectin [5]

Taxonomy of the *Chlorophyta*

- division (phylum) of *Chlorophyta* closely related to the land plants, i.e. the *Bryophyta* & *Tracheophyta* based on the given characteristics

- ~ 500 genera with ~ 8000 species

- habitat distribution: mostly freshwater (~ 90 %) and only ~ 10 % marine species, but some groups (e.g. *Ulvophyceae*) solely marine

Classification of the *Chlorophyta*

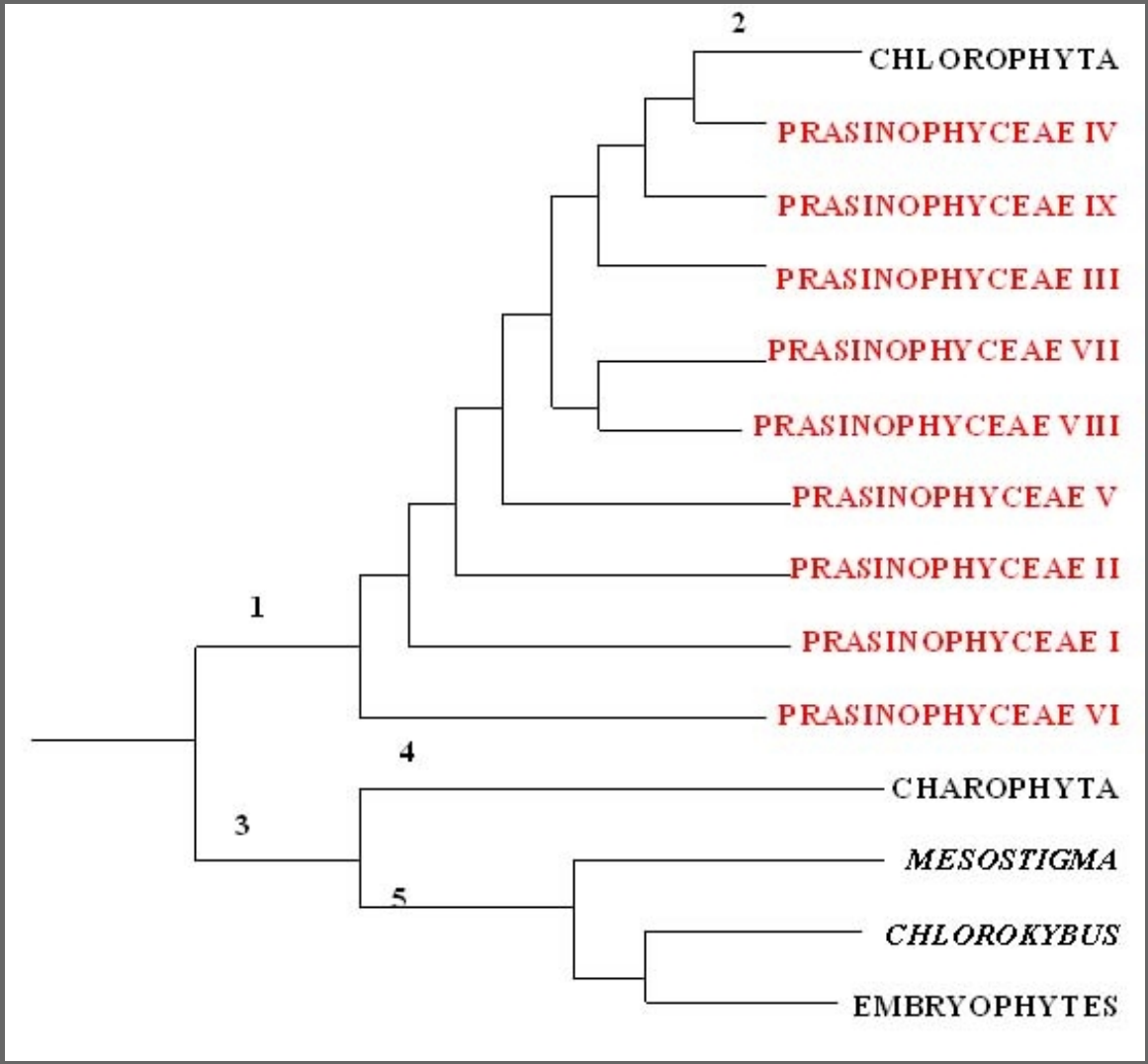
- classical approach deploys thallus organization
  monadal/unicellular, coccoid, palmelloid colonies, sarcinoid, filamentous, thallose, siphonous

  authors: Bold & Wynne

- modern approach based on ultrastructural research and molecular characteristics

  authors: Mattox, Stewart, Pickett-Heap, van den Hoek, Graham & Wilcox, Marin & Melkonian

Classification of the *Chlorophyta* II



1. CHLOROBIONTS, including clades of the PRASINOPHYTES
2. CHLOROPHYTE clade
3. STREPTOBIONT clade
4. CHAROPHYTE clade
5. EMBRYOPHYTE clade

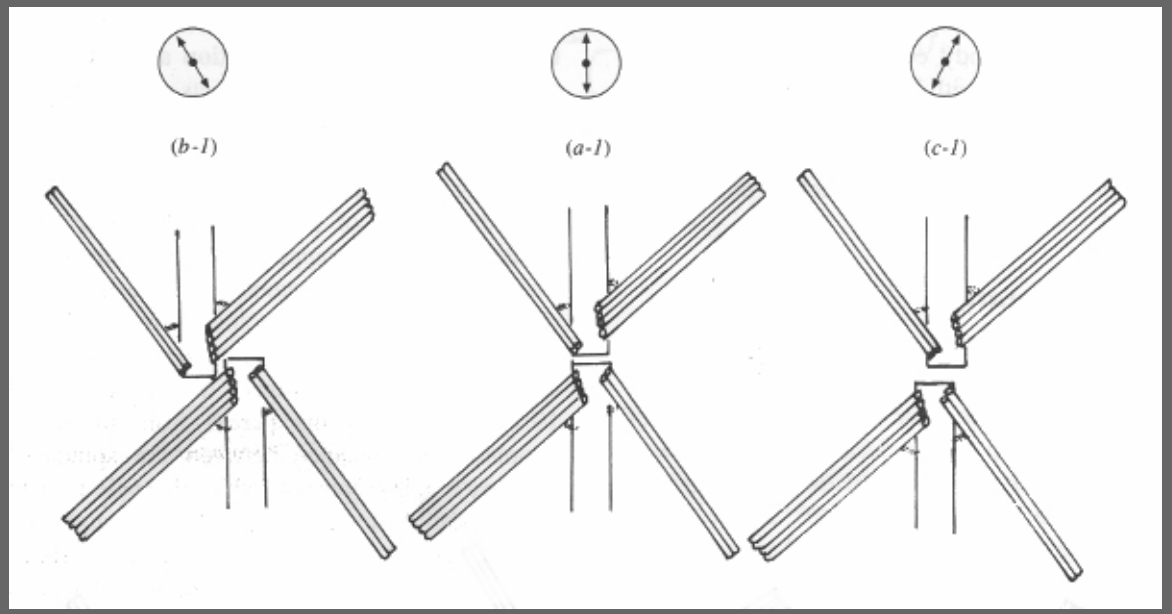
cladogramm after Proschold and Leliaert (2007) [20]

Classification by Molecular & Ultrastructural Evidences

- ultrastructure of flagellar root
- differences in mitosis & cytokinesis
- rRNA/rDNA sequence comparison
- key enzymatic pathways

Flagellar Roots

characterization of 'chlorophyceaen' classes by the arrangement of the basal bodies of the flagella:

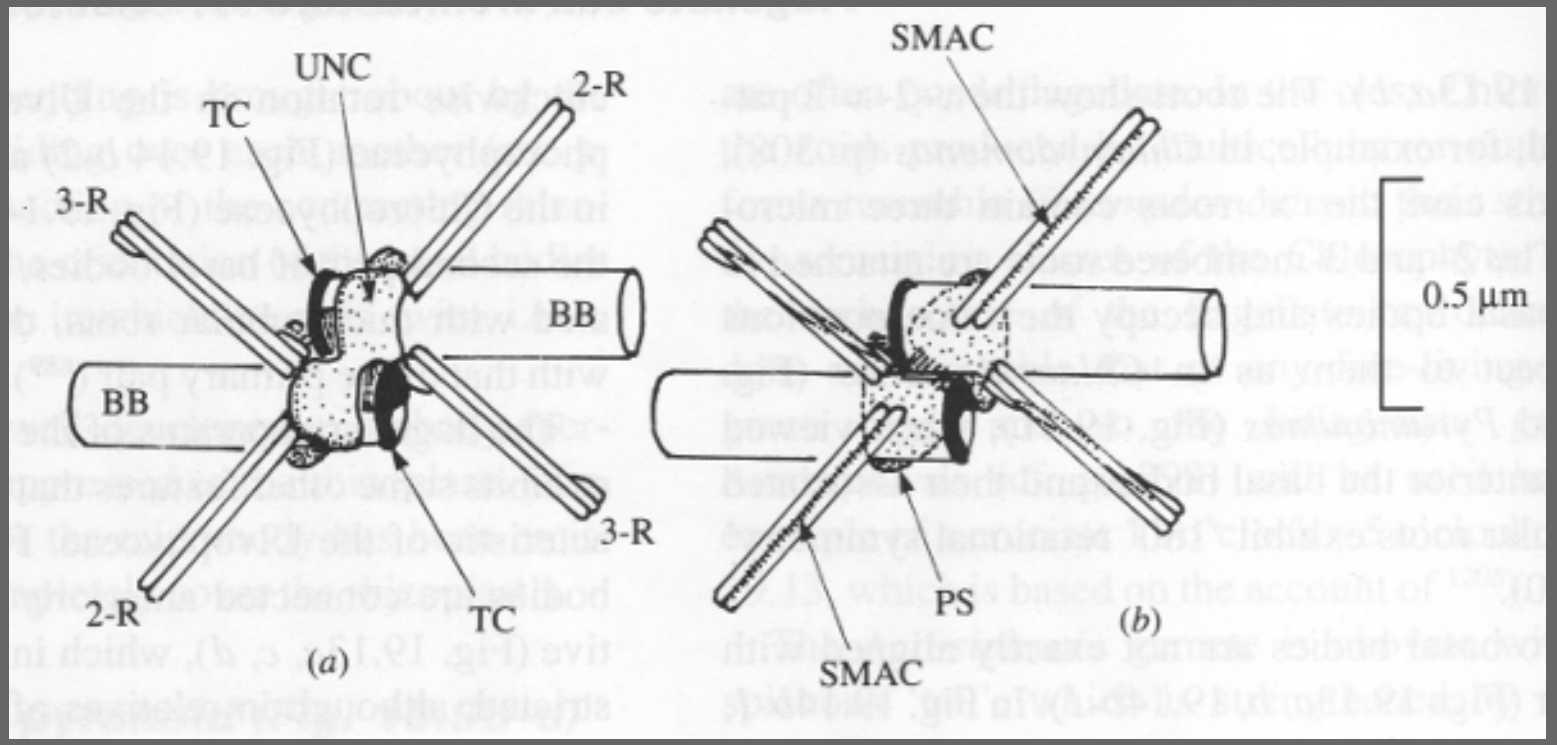


left: 11 o'clock – 5 o'clock type (*Ulvophyceae*)
center: 12 o'clock – 6 o'clock type, proposed ancestral type
right: 1 o'clock – 7 o'clock type (*Chlorophyceae*) [1]

Flagellar Roots

cruciate flagellar roots with x-2-x-2 arrangement of microtubular roots:

11 o'clock – 5 o'clock type (*Ulvophyceae*)

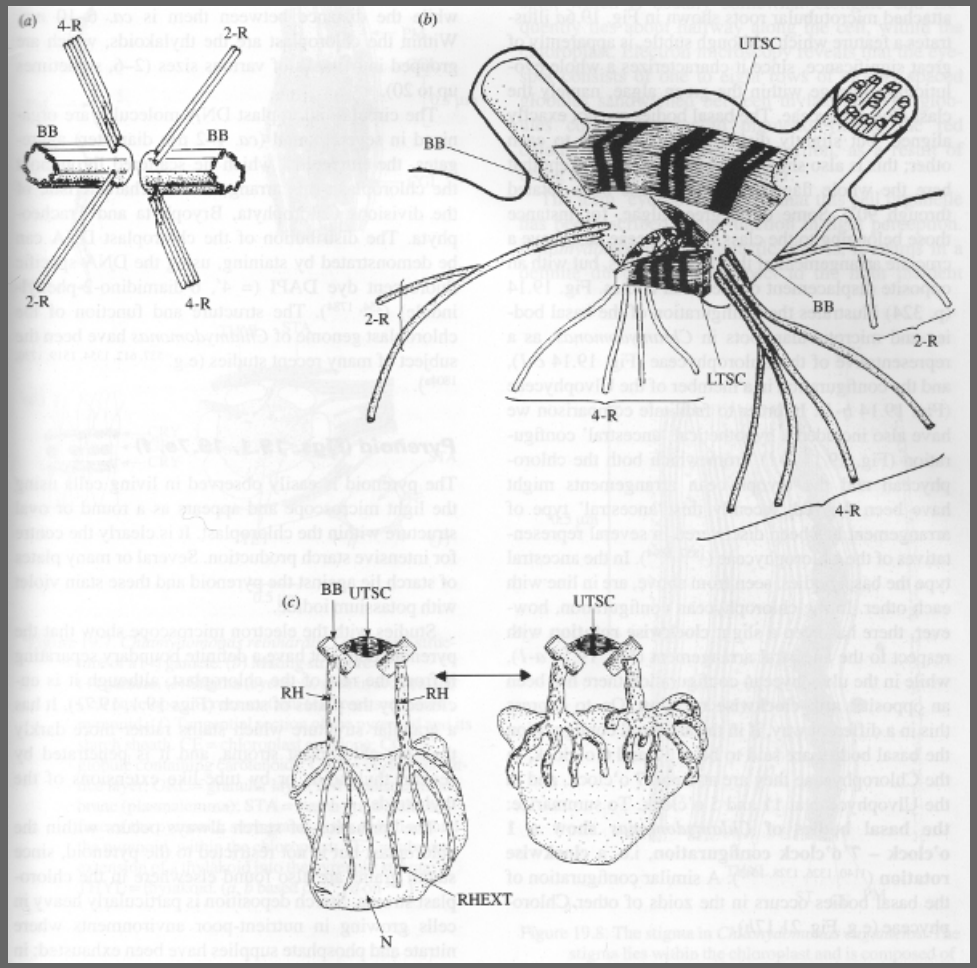


Acrosiphonia sp. flagellar roots [1]

Flagellar Roots

cruciate flagellar roots with x-2-x-2 arrangement of microtubular roots:

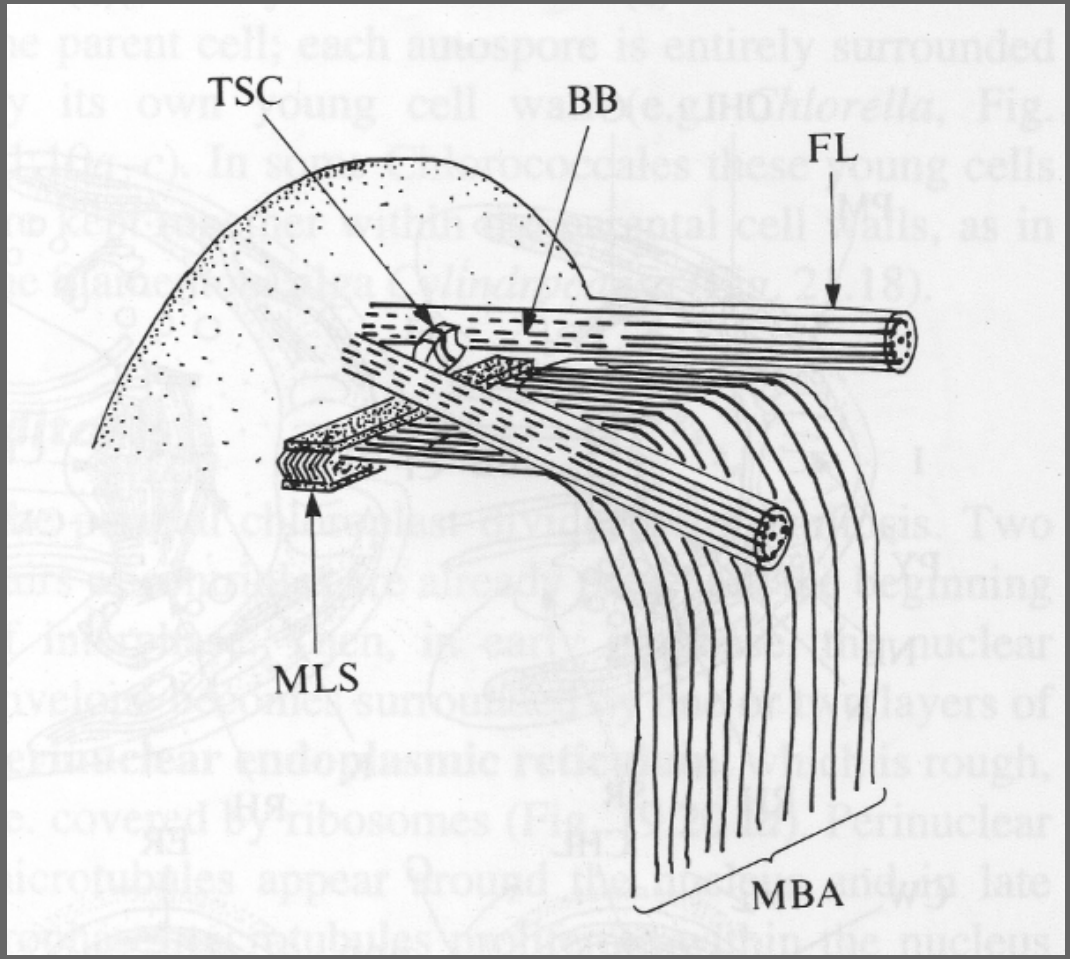
1 o'clock – 7 o'clock type (*Chlorophyceae*)



Chlamydomonas reinhardtii, flagellar roots, rhizoplasts

Flagellar Roots

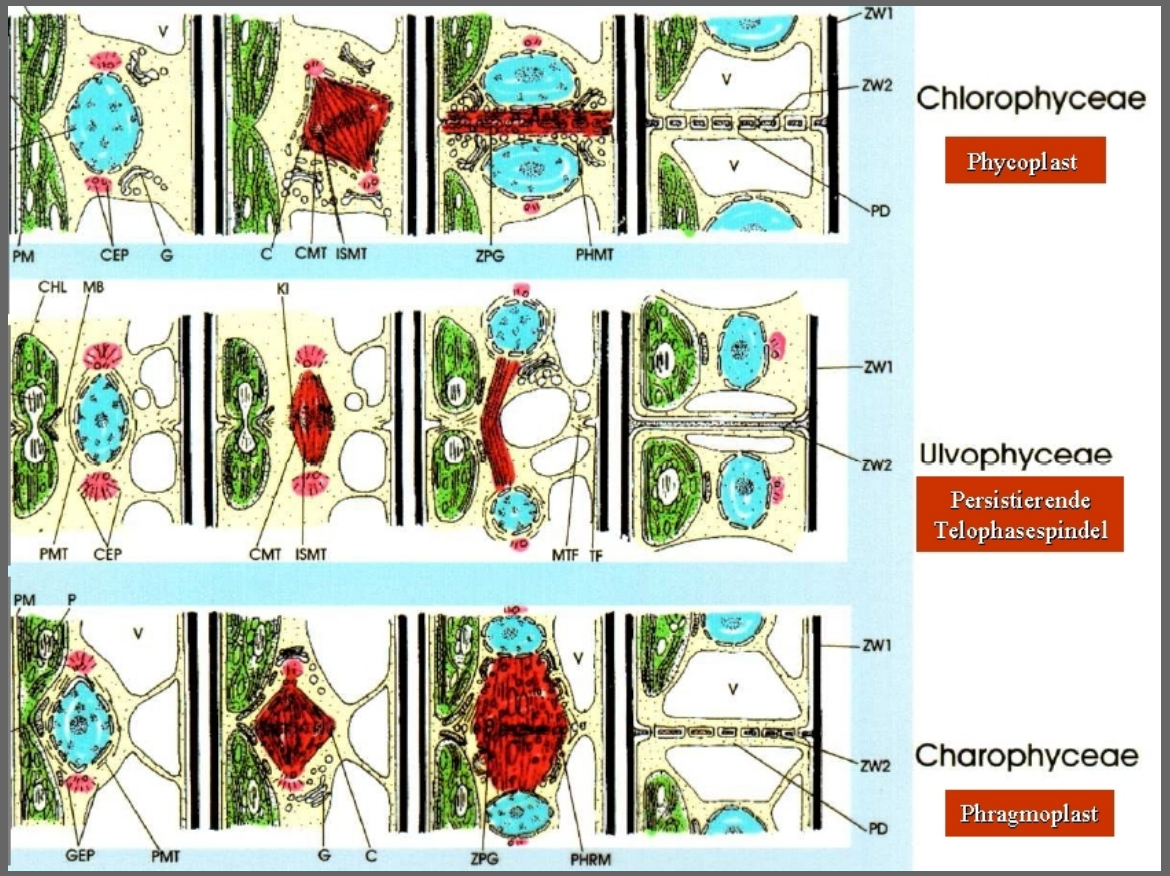
unilateral type (Charophyceae)



Chaetosphaeridium sp. flagellar roots [1]

Mitosis & Cytokinesis

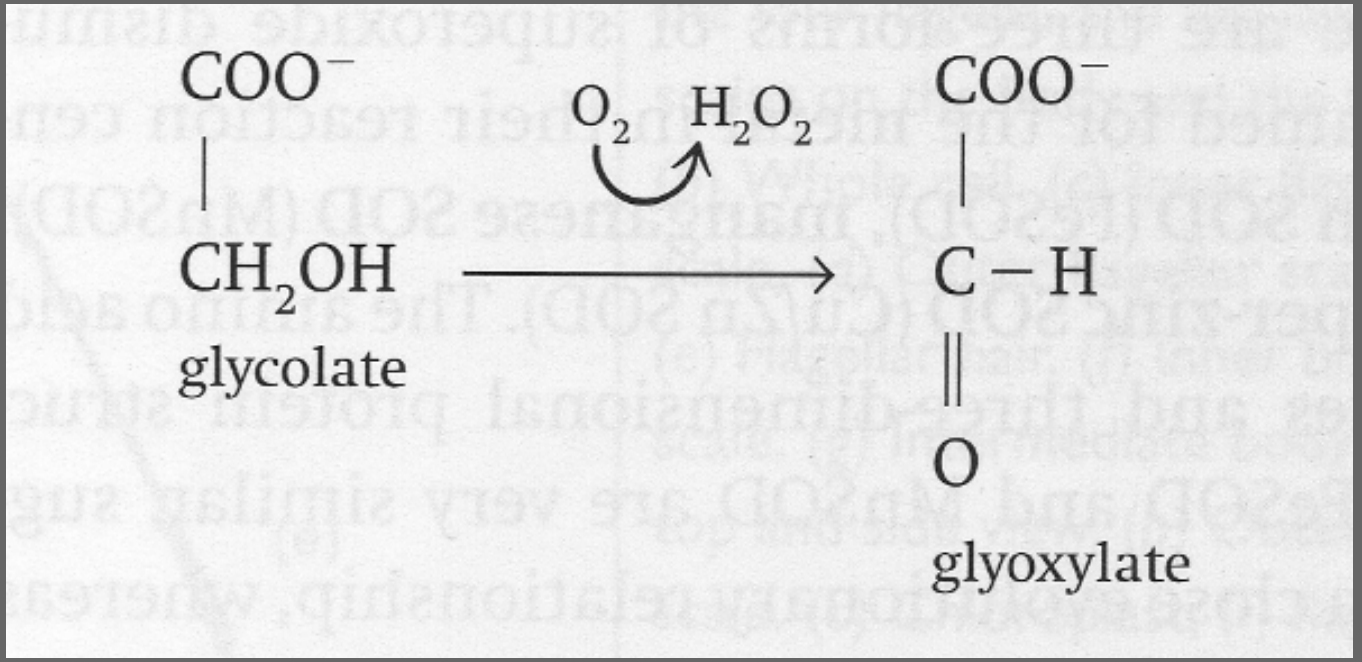
- open vs. closed mitosis
- persistent vs. non-persistent telophase spindle
- form of cytokinesis:
  - cleavage furrow
  - phycoplast
  - phragmoplast



mitosis & cytokinesis [1] altered by Menzel

Enzymatic Pathways

- glycolate oxidation



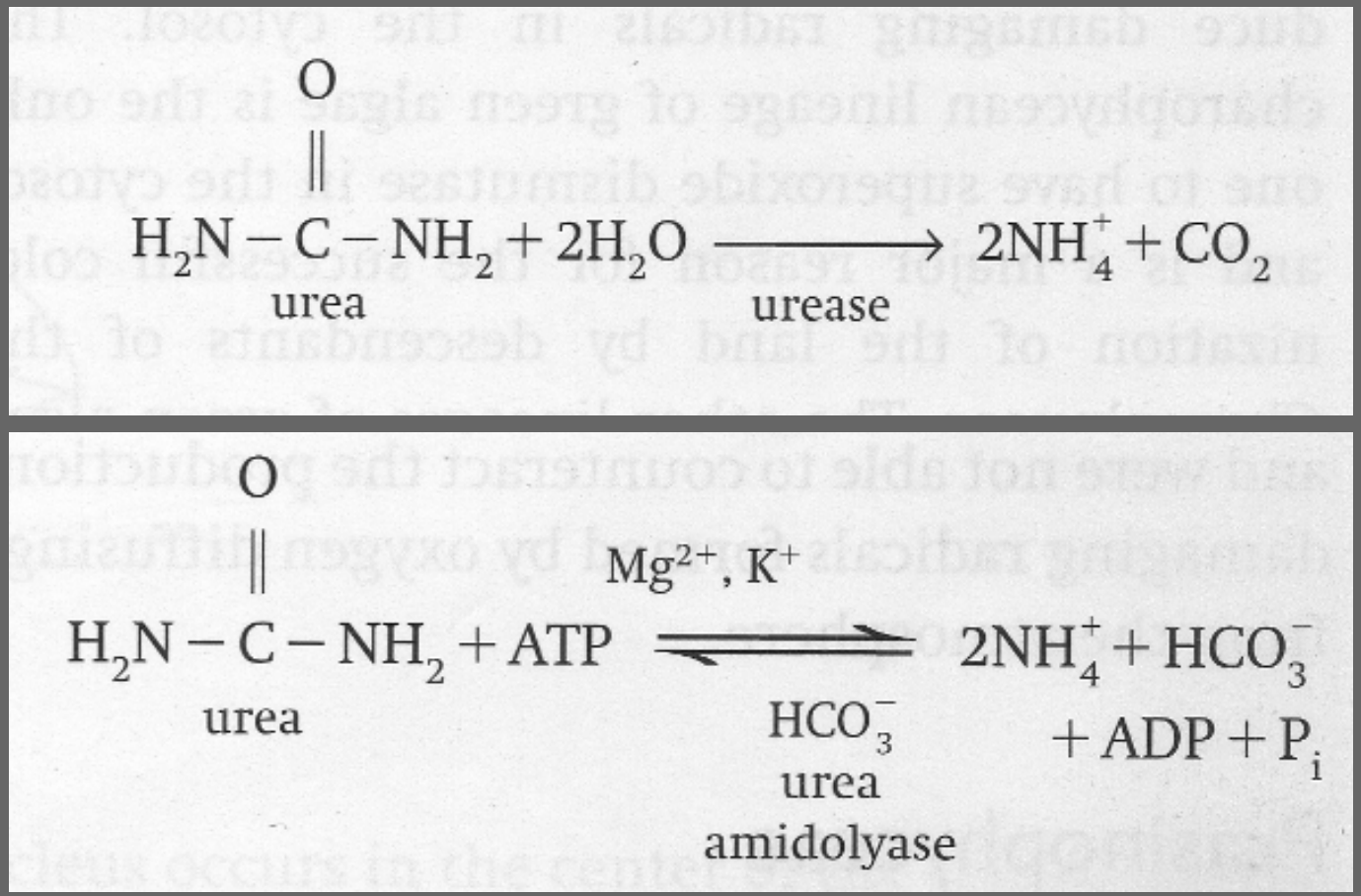
glycolate reaction [2]

glycolate dehydrogenase: *Chlorophyceae*, *Ulvophyceae*
glycolate oxidase: *Charophyceae*

Enzymatic Pathways

- urea desamination

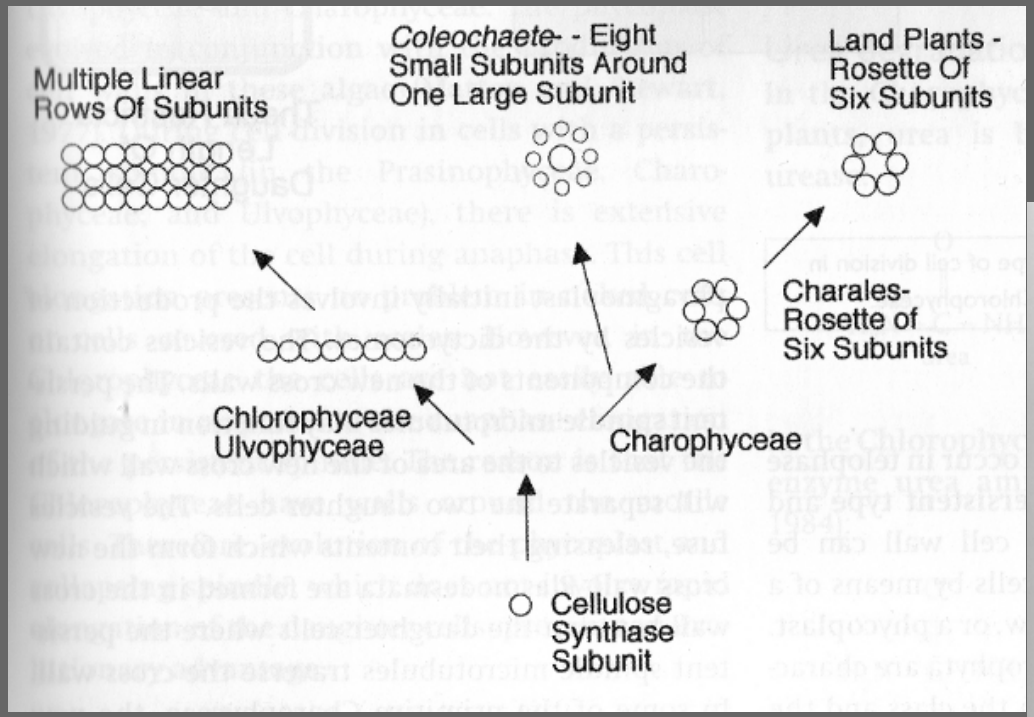
urease: *Charophyceae*, *Ulvophyceae*
urea amidolyase: *Chlorophyceae*



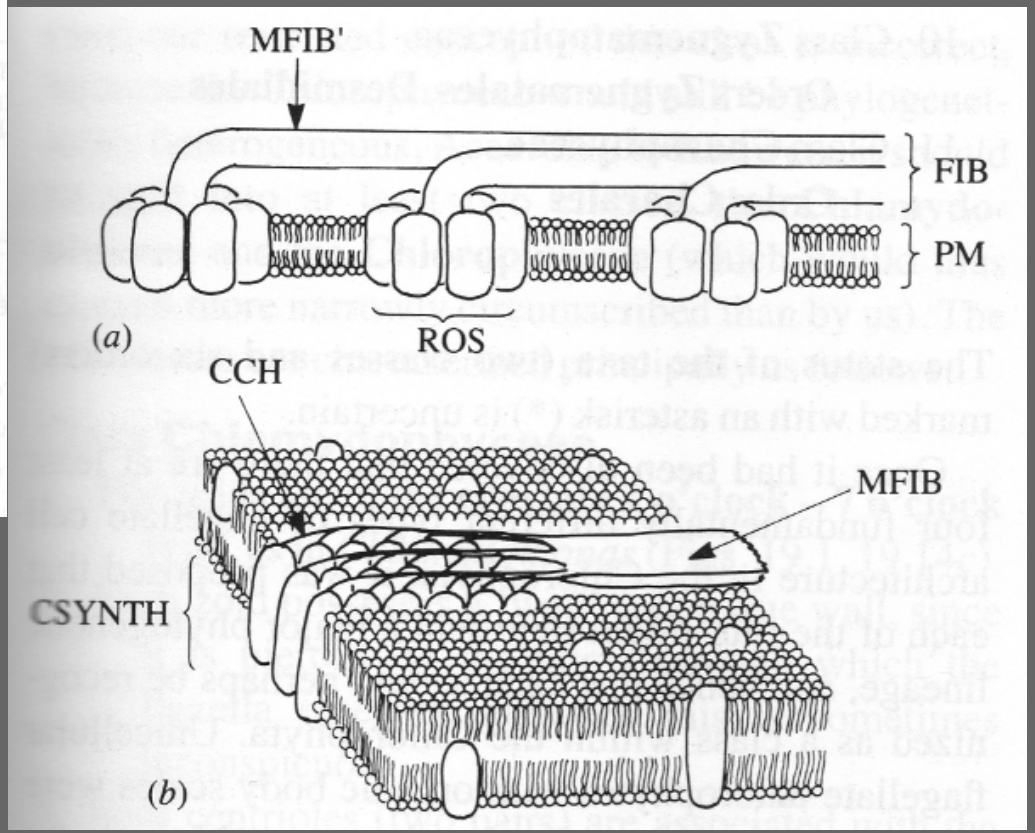
urea reaction [2]

Enzymatic Pathways

- cellulose synthase



evolution of cellulose synthase [2]



forms of cellulose synthase [1]

Classes of the *Chlorophyta*

4 classes (classis):

- *Prasinophyceae*
- *Ulvophyceae*
- *Chlorophyceae*
- *Charophyceae*

Prasinophyceae

Morphology:

- unicellular, free-living, primitive green flagellates
- 1-8 flagella of varied morphology
- flagella usually inserted in a lateral or apical depression

Habitat:

- marine and freshwater habitats
- important part of phytoplankton (picoplankton)

Special features:

- organic scales on flagella and plasmalemma
- fossil findings ~ 1.2 billion years old (Precambrium)

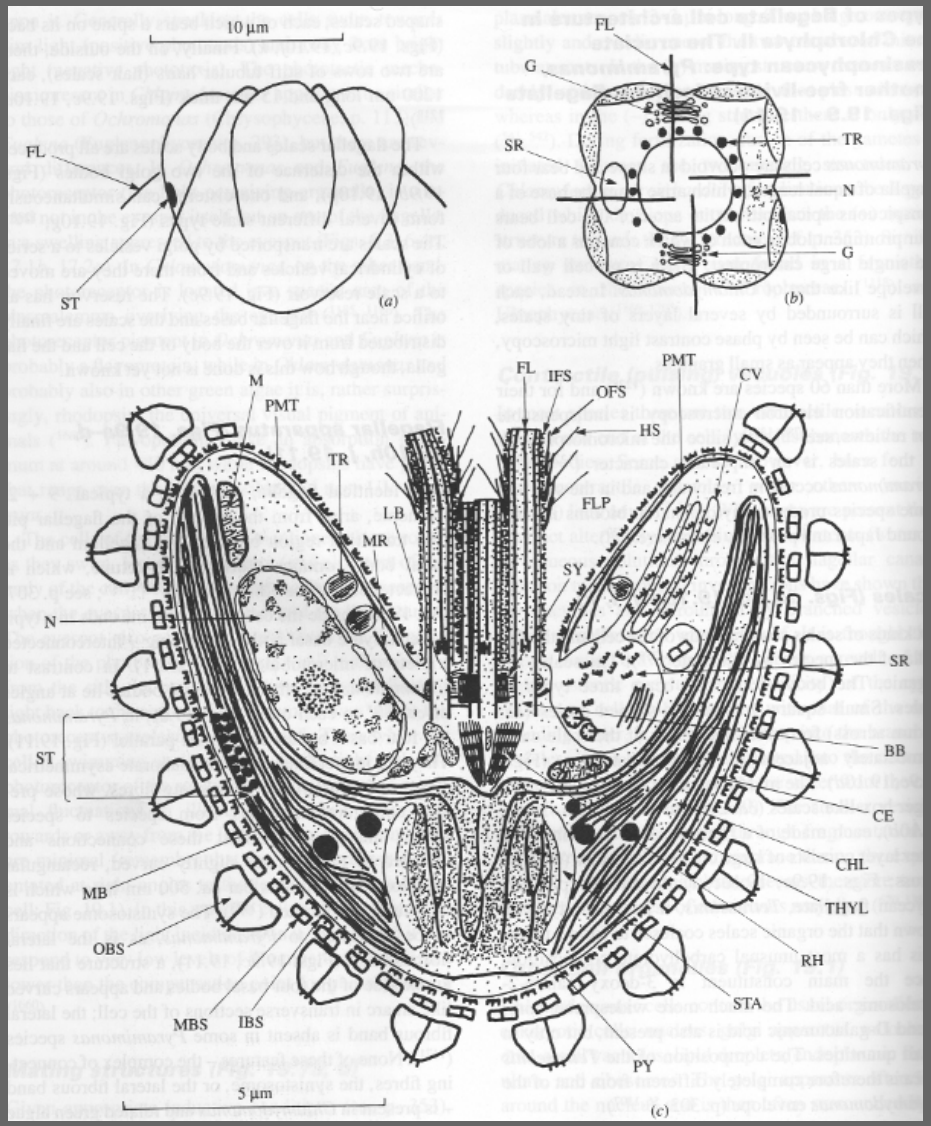
Cell division:

- open or closed mitosis
- persistent or non-persistent telophase spindle
- cytokinesis by cleavage furrow or phycoplast

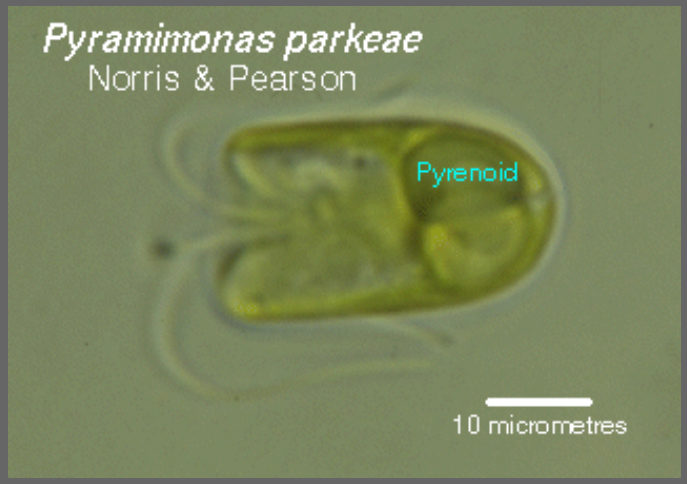
Prominent species:

- *Tetraselmis*, *Pyramimonas*, *Ostreococcus*

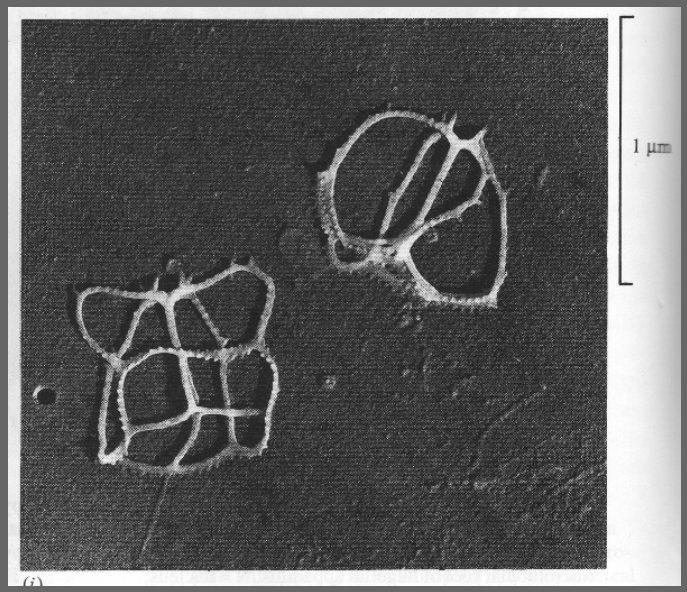
Pyramimonas



Pyramimonas lunata [1]



[6]



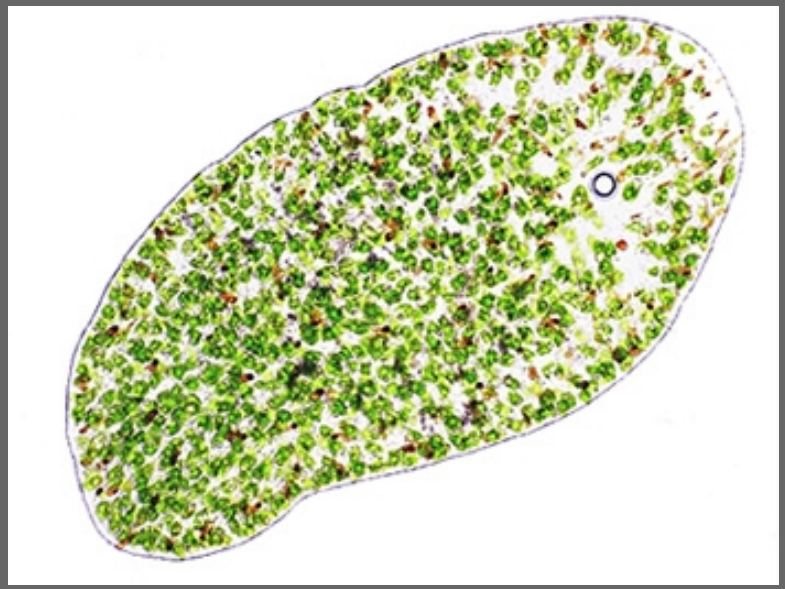
Pyramimonas lunata
scanning electron micrograph
outer body scales [1]

Tetraselmis

symbiosis between flatworm
Convoluta roscoffensis and *Tetraselmis*

Tetraselmis sueccia [4]

flatworm *Convoluta roscoffensis* [7]



flatworm *Convoluta roscoffensis* [7]

Ulvophyceae

Morphology:
- unicellular, multicellular, siphonocladous non-flagellates
- zoids with 2 - 4 flagella of 11 o'clock – 5 o'clock type

Molecular features:
- glycolate dehydrogenase, urease
- linear complexes of cellulose synthase

Habitat:
- almost exclusively marine

Cell division:
- closed mitosis
- persistent telophase spindle
- cytokinesis by cleavage furrow

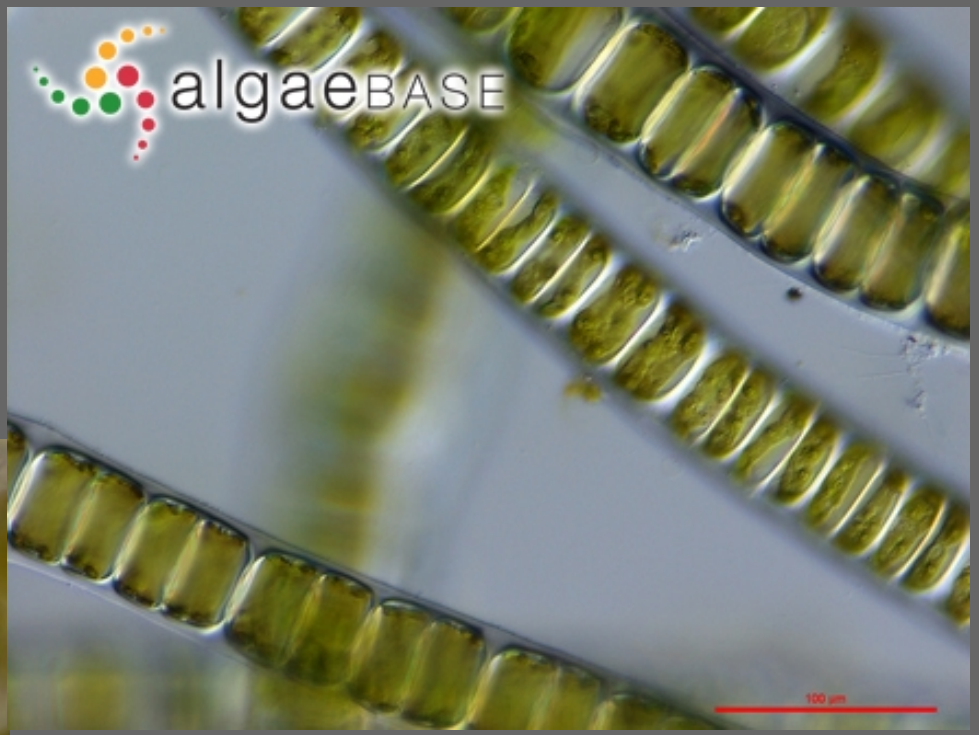
Reproduction:
- haplontic or isomorphic diplohaplontic life cycle
- isogamous or anisogamous sexual reproduction

Orders of *Ulvophyceae*

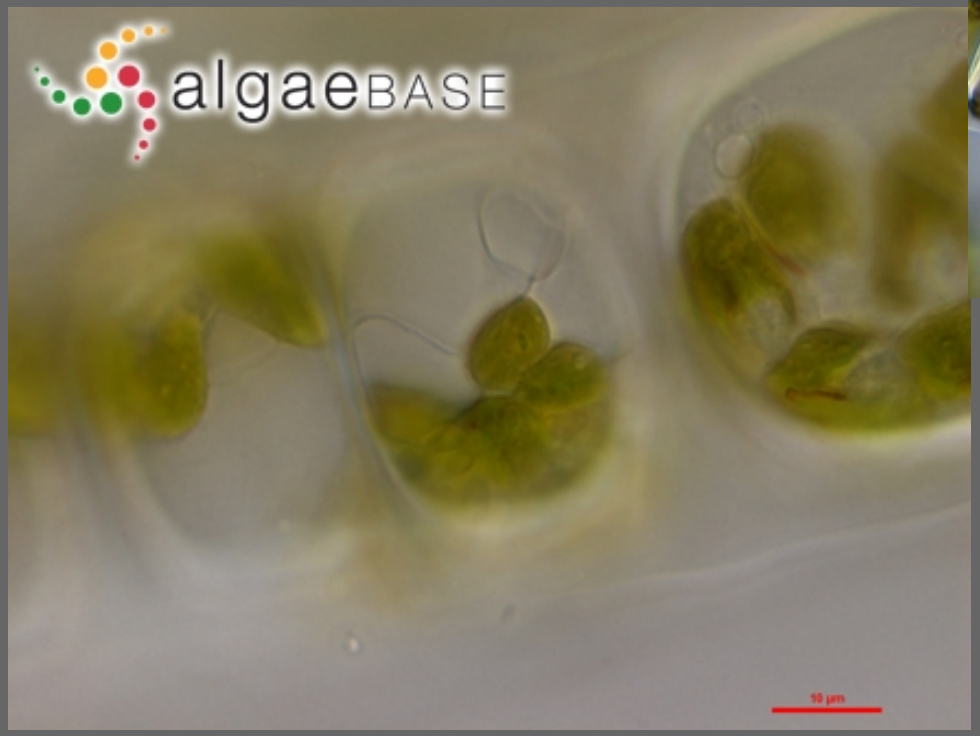
- *Ulotrichales*
- *Ulvales*
- *Cladophorales*
- *Dasycladales*
- *Caulerpales*
- *Siphonocladales*

Ulotrichales

- uninucleate
- unbranched filaments
- quadriflagellate zoospores
- biflagellate gametes
- isogamous
- freshwater habitats



Ulothrix zonata [3]



Ulothrix zonata [3]

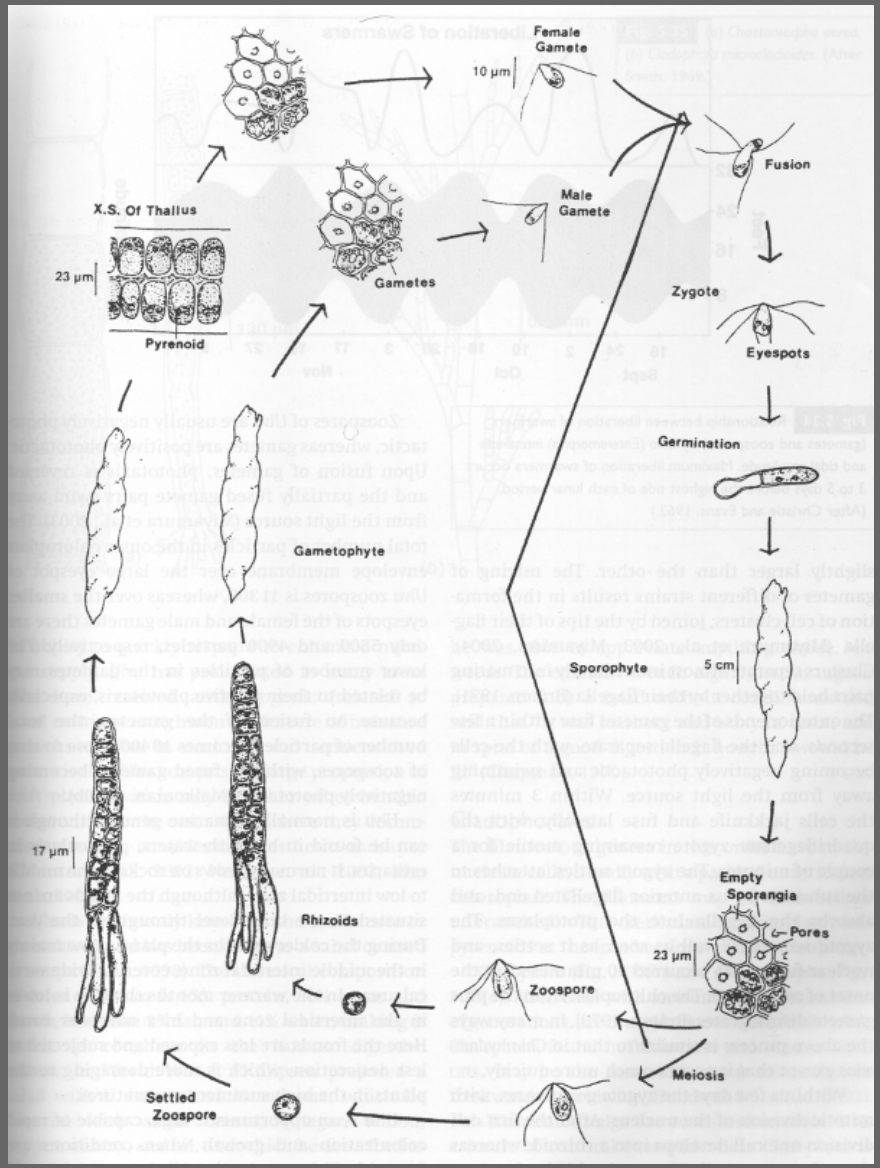
Ulvales

- thallose
- polymorph
- quadriflagellate zoospores
- biflagellate gametes
- marine habitats
- *Ulva* used as food source

Ulva rigida [3]

Ulva rigida [3]

Ulvales II



Ulva sp. life cycle [2]

Cladophorales

- multinucleate
- branched or unbranched filaments
- parietal / reticulate chloroplast
- marine & freshwater habitats

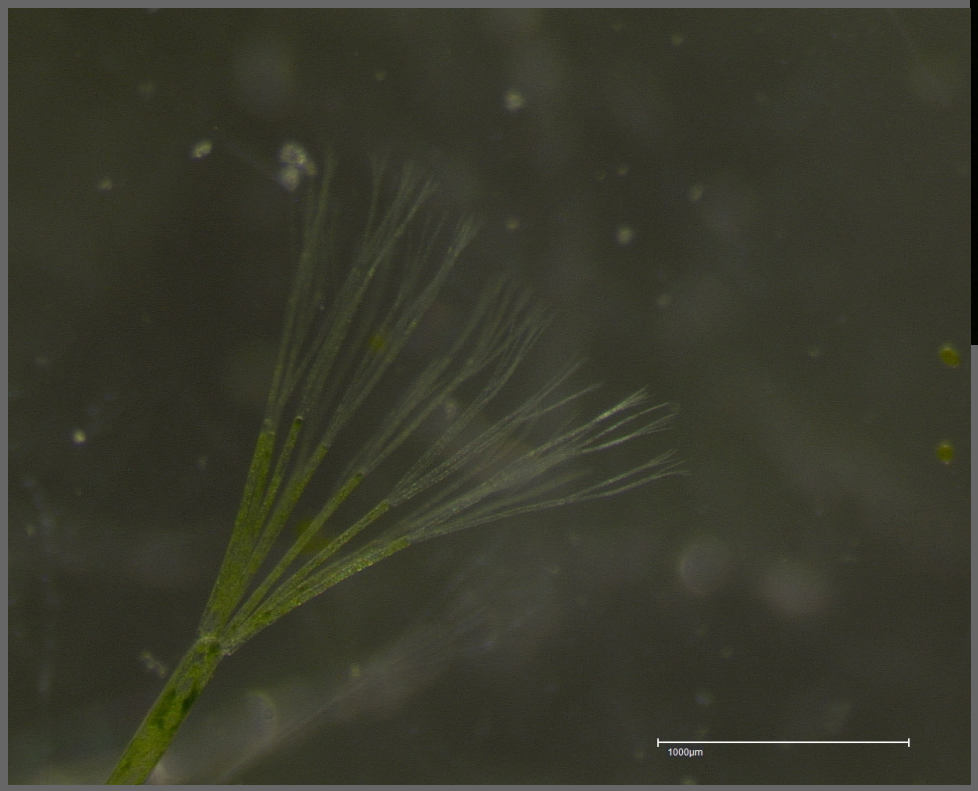
Cladophora glomerata [3]

Cladophora sakaii [3]

Dasycladales

- uninucleate vegetative stage
- multinucleate generative stage
- mostly calcified
- fossil records of ~ 570 million yrs. (Precambrian/Cambrian boundary)
- isogamous
- marine, (sub)tropical habitats

Acetabularia peniculus, cyst stage [21]



Acetabularia acetabulum, vegetative stage [21]

Caulerpales

- coenocytic (siphonaceous)
- non-septate thalli
- amyloplasts
- siphonoxanthin, siphonein
- no cellulose (xylan, mannan)
- marine habitats

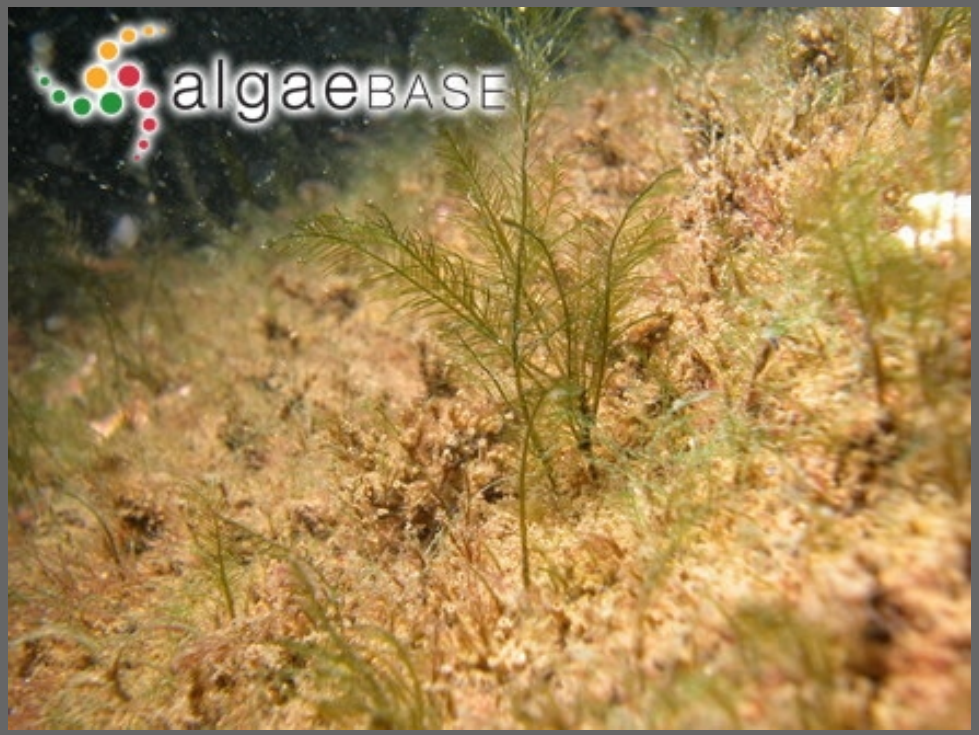
Codiaceae, Codium fragile, sporangia [3]

Codiaceae, Codium fragile [3]

Codium – *Azotobacter* symbiosis with nitrogen-fixation

chloroplasts survive outside of *Codium* in predators, e.g. *Elysia*

Caulerpales II



Derbesiaceae, Bryopsis hypnoides [3]

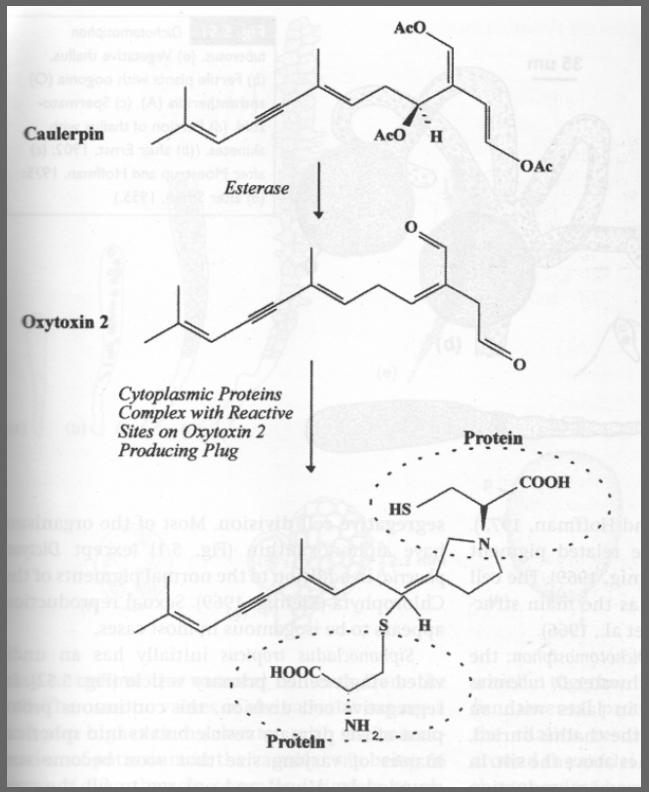
Derbesiaceae
- stephanokont zoospores

Codiaceae, Udotea glaucescens [3]

Codiaceae
- biflagellate zoospores

Caulerpales III

Caulerpa
- anisogamous
- amyloplasts
- special wound healing process involving oxytoxin 2, a dialdehyde
- asexual reproduction by thallus fragmentation



oxytoxin 2 [2]

Caulerpaceae, Caulerpa articulata [3]

Siphonocladales

- multinucleate
- multicellular, thallose
- reticulate chloroplasts
- siphonoxanthin
- segregative cell division
- isogamous
- marine, tropical habitats

Valonia utricularis [3]

Valonia utricularis, zoospore formation [3]

Valonia
- model organism for vacuole research

Chlorophyceae

Morphology:

- great variety in morphology
- zoids with 2 or 4 flagella of 1 o'clock – 7 o'clock type

Molecular features:

- glycolate dehydrogenase, urea amidolyase
- linear complexes of cellulose synthase

Habitat:

- predominately freshwater habitats

Cell division:

- closed mitosis
- non-persistent telophase spindle
- cytokinesis by septum within phycoplast

Reproduction:

- haplontic life cycle
- isogamous, anisogamous or oogamous sexual reproduction

Orders of *Chlorophyceae*

- *Volvocales*
  - *Chlamydomonadaceae*
  - *Dunaliellaceae*
  - *Volvocaceae*
- *Tetrasporales*
  - *Tetrasporaceae*
  - *Palmellaceae*
- *Prasiolales*
- *Chlorellales*
- *Trebouxiales*
- *Sphaeropleales*
- *Chlorosarcinales*
- *Chaetophorales*
- *Oedogoniales*

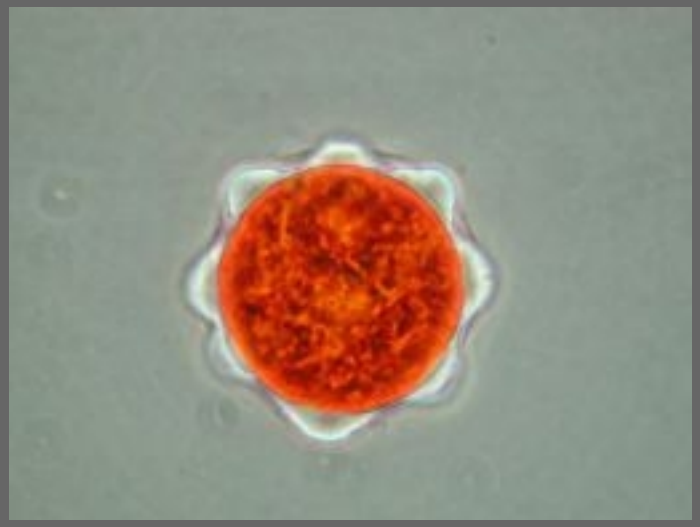
Volvocales – *Chlamydomonaceae* I

- uninucleate
- unicellular
- biflagellate
- cup-shaped chloroplast
- central pyrenoid
- isogamous, anisogamous, oogamous
- freshwater & terrestrial habitats
- model organism

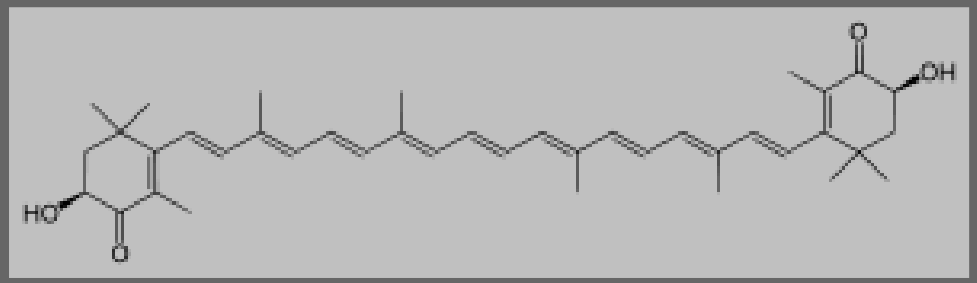
Chlamydomonas sp. [4]

Volvocales – *Chlamydomonaceae* II

red snow on Gulkana Glacier in the Alaska Range, USA



Chlamydomonas nivalis left, center [8], right [9]

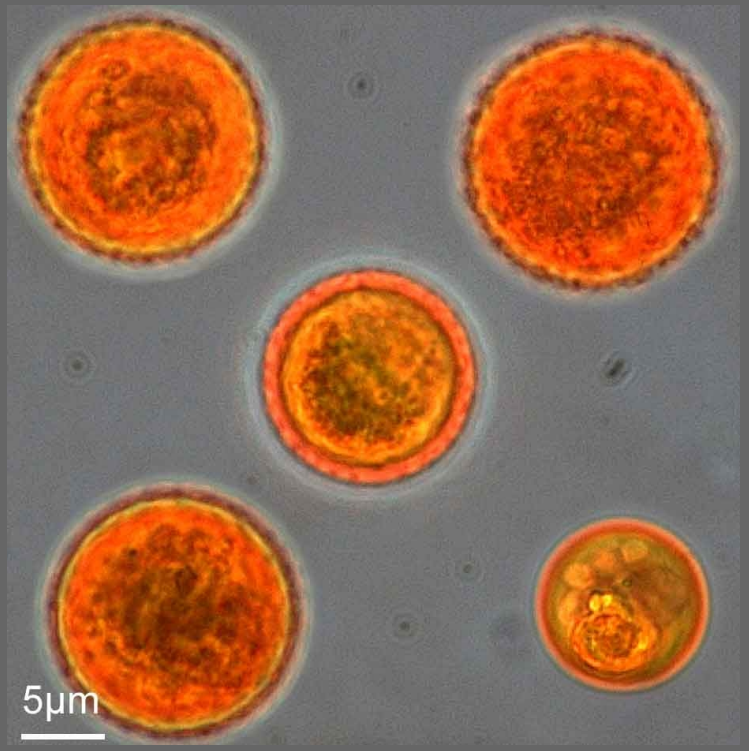


astaxanthin [5]

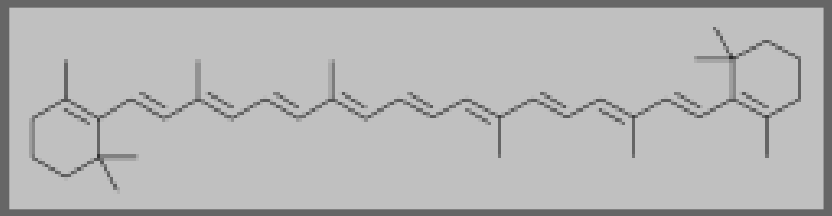
Volvocales – Dunaliellaceae

- halophil species, optimal growth at NaCl of > 0.5 M
- probably most halotolerant eukaryote
- used as producer of β-carotene
- acidophil species, optimal growth at pH 1 !

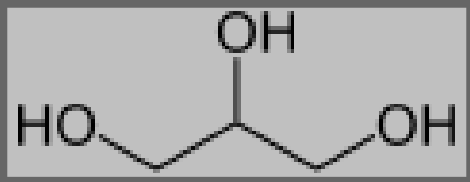
biomass growth ponds, Australia [10]



Dunaliella salina [11]



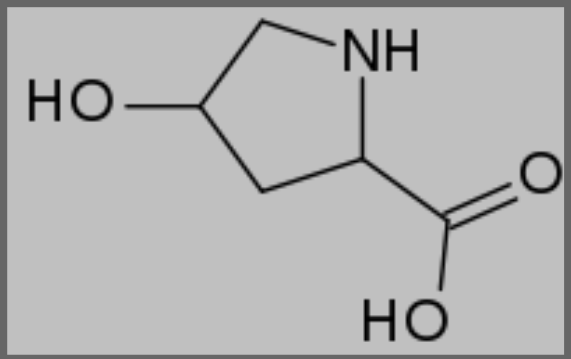
β-carotene [5]



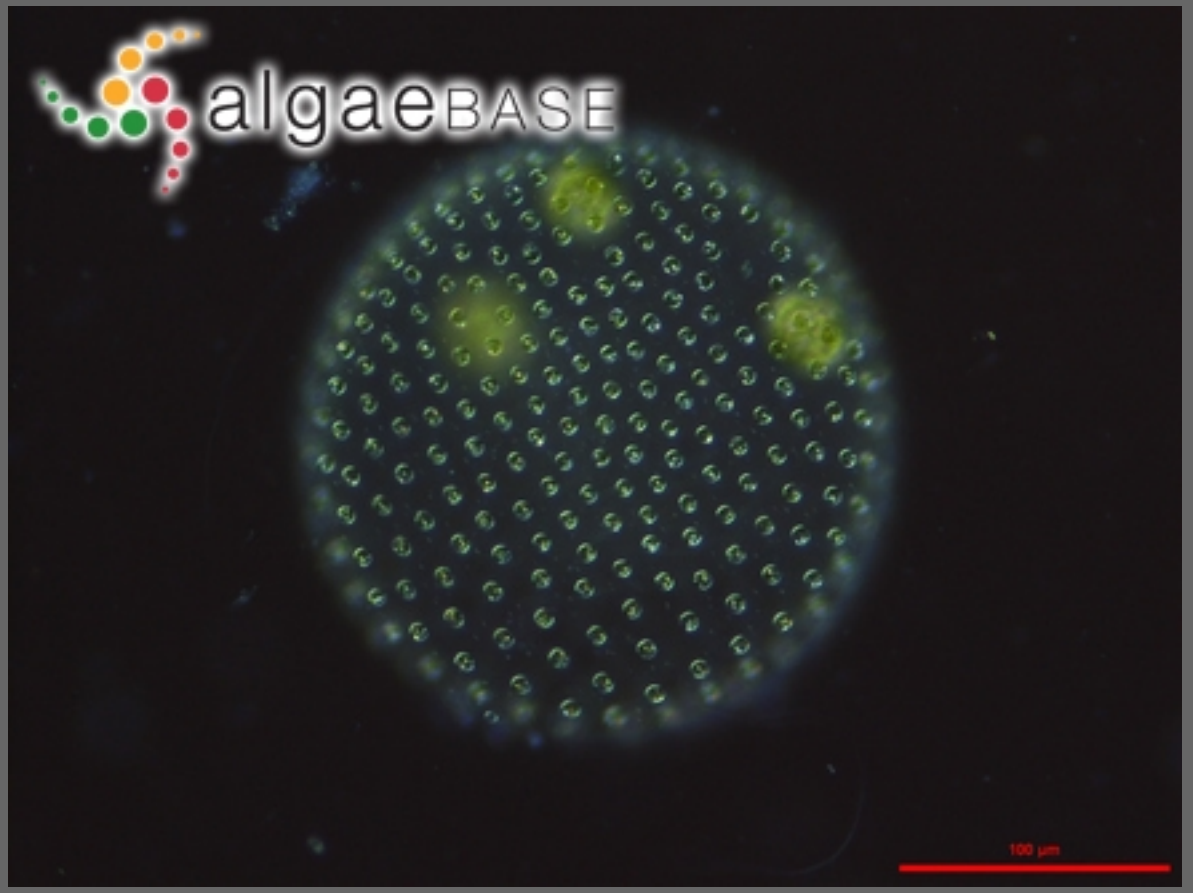
glycerol [5]

Volvocales - *Volvocaceae*

- uninucleate
- multicellular, colonial
- glycoprotein sheath (ecm)
- oogamous
- mostly freshwater habitats

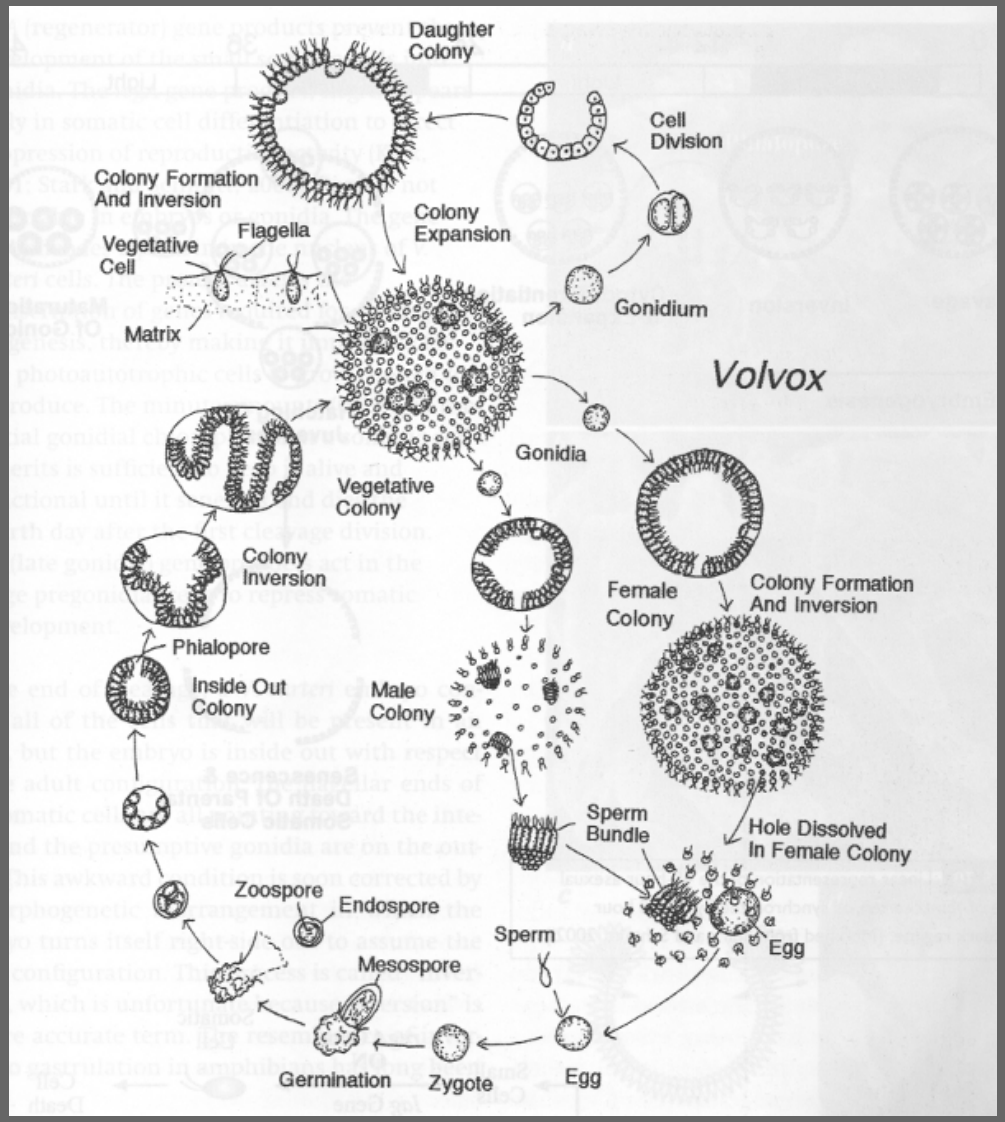


hydroxyproline [5]

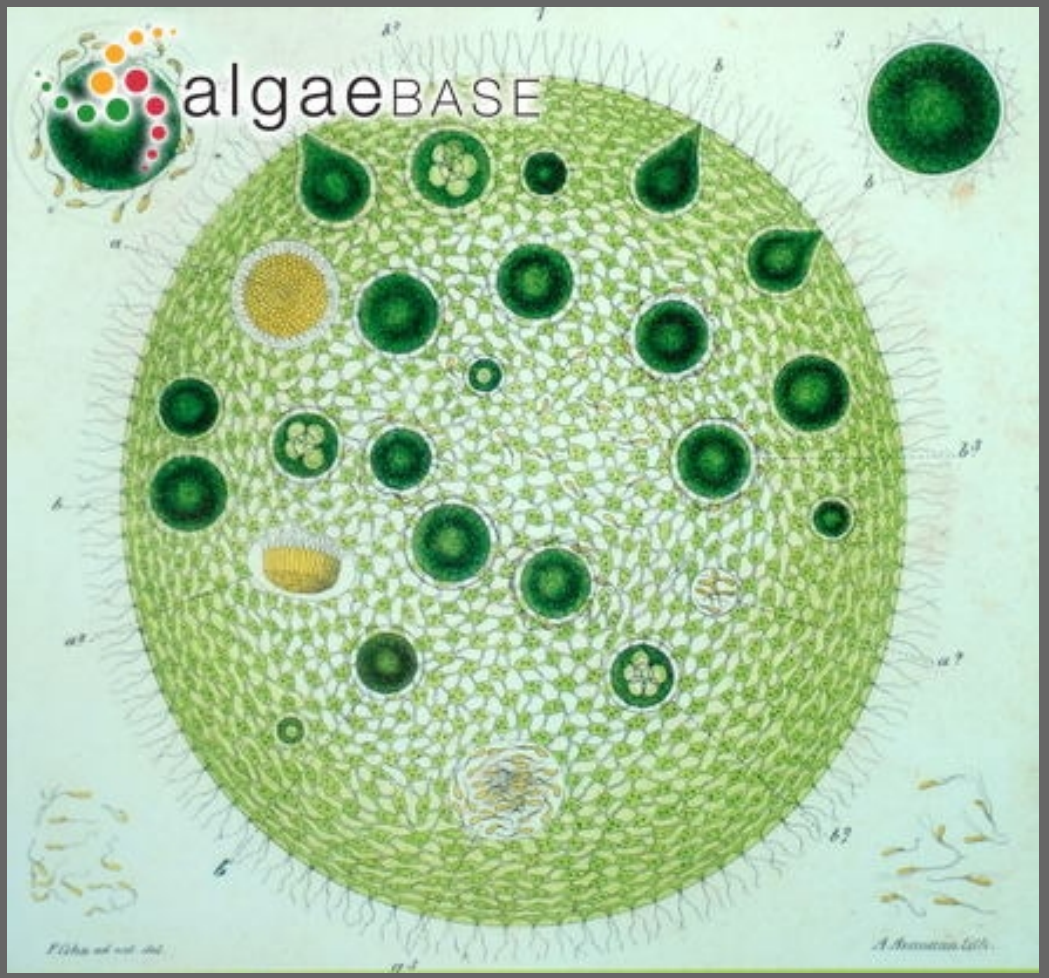


Volvox aureus [3]

Volvocales – *Volvocaceae* II



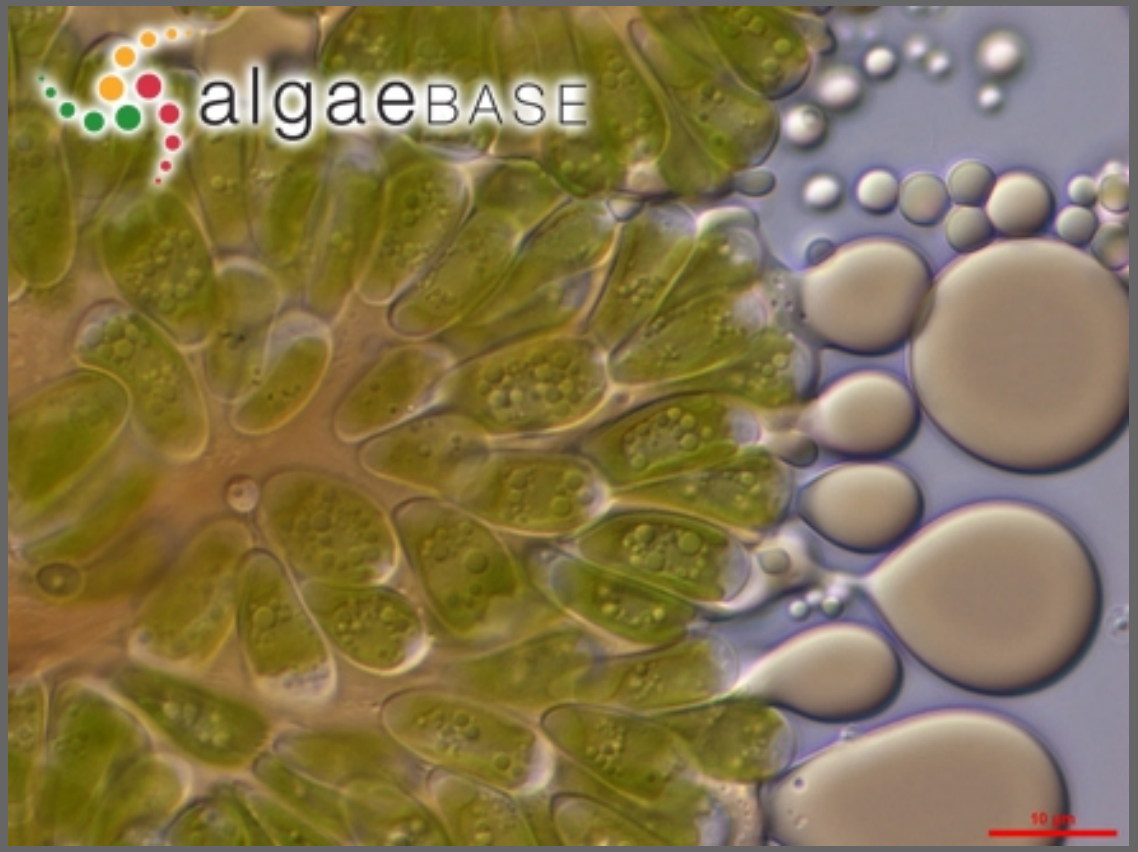
life cycle of *Volvox carteri* [2]



Volvox globator [3]

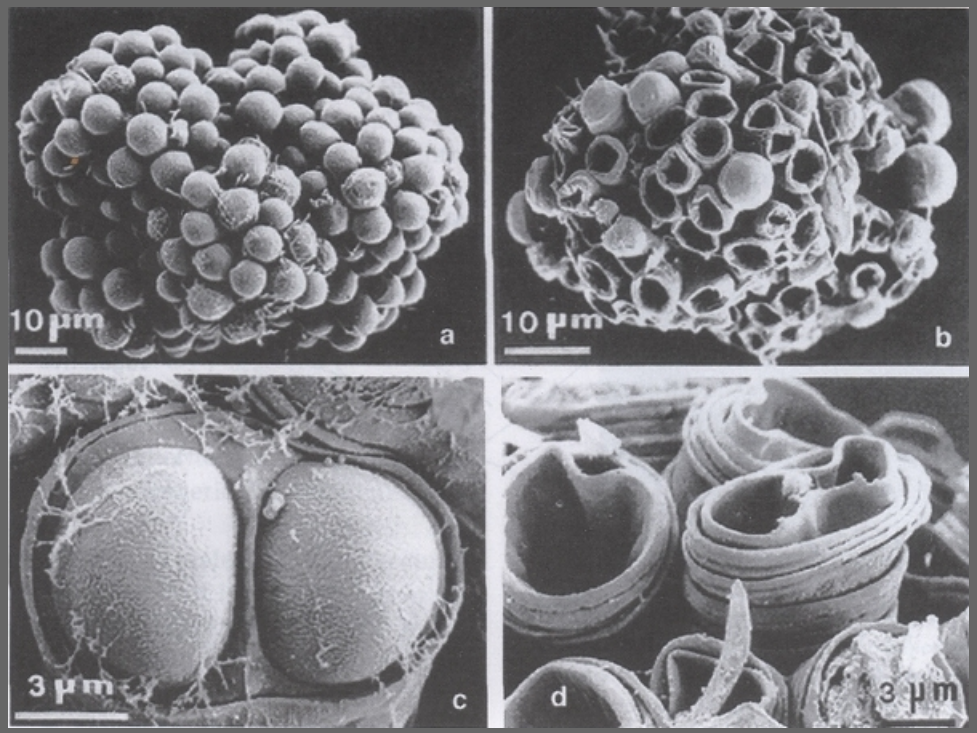
Tetrasporales

- non-motile
- non-filametous colonies
- no cell division of vegetative cells
- pseudocilia in *Tetrasporaceae*
- isogamous
- freshwater habitat



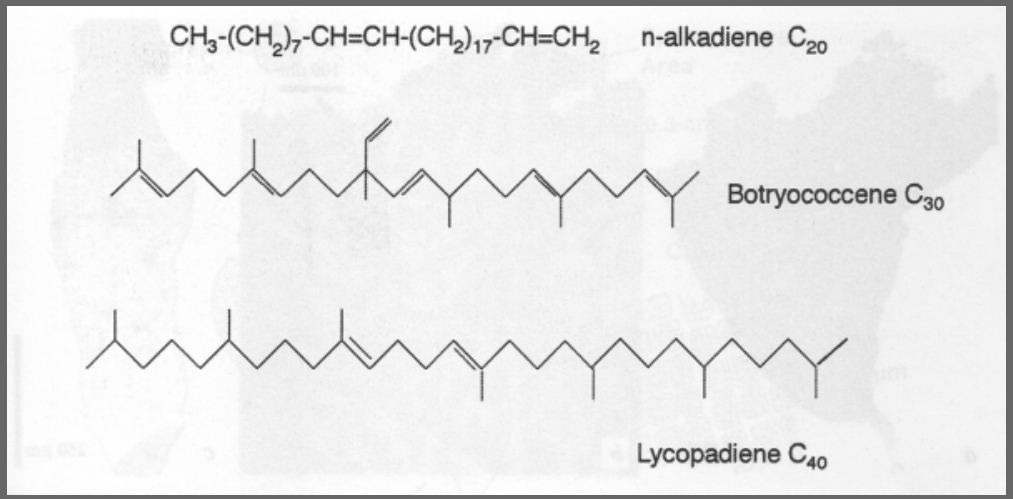
Botryococcus braunii [3]

Tetrasporales II



Botryococcus braunii
scanning electron micrographs of colonies [2]

- *Botryococcus* and other species researched for biofuel capabilities
- up to 70 % of dry weight as alkadienes



botryococcene [2]

Prasiolales

- uninucleate
- multicellular
- stellate chloroplasts
- central pyrenoid
- freshwater, marine, terrestrial habitats

Prasiola stipiata, sporophyte [3]

Prasiola stipiata, habitus [3]

Prasiolales II

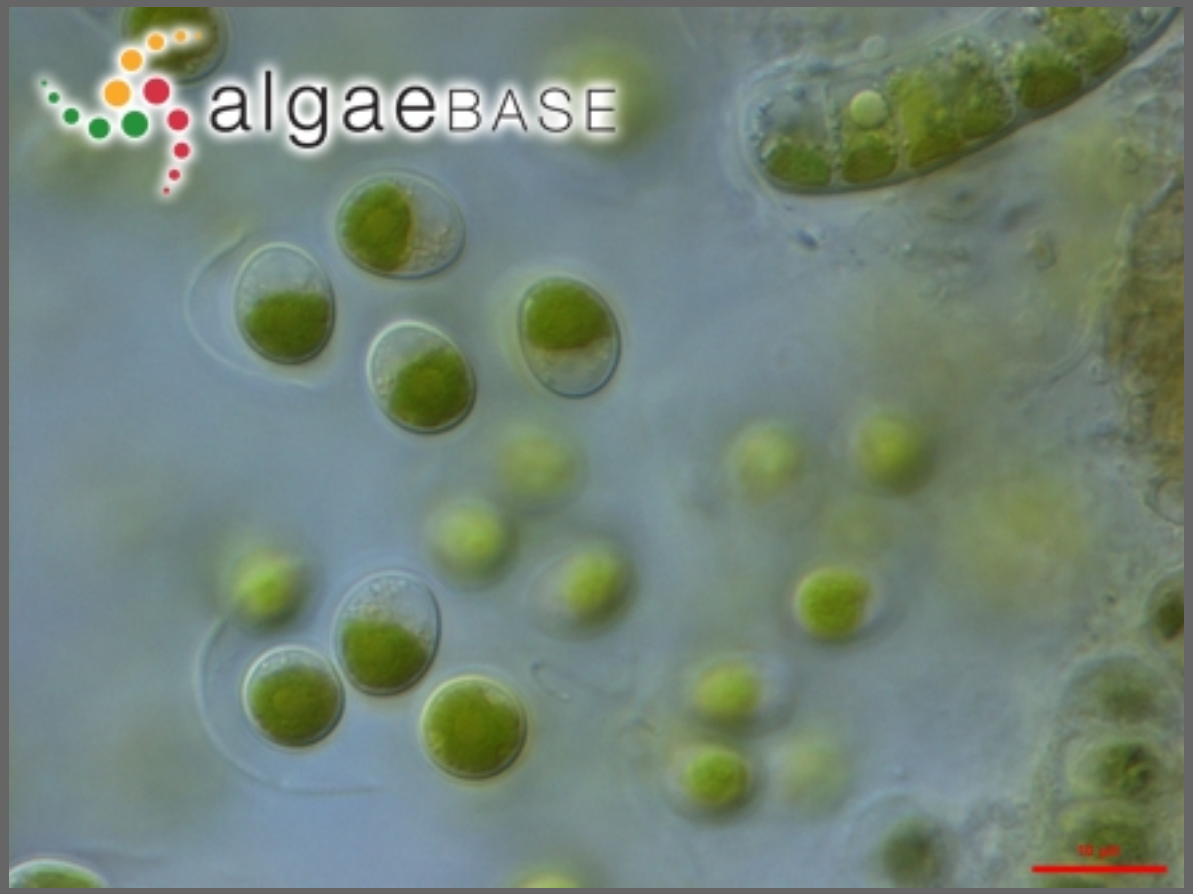
Prasiola stipiata
- special life cycle
- homothallic
- formation of haploid gametes on diploid thallus

Prasiola stipiata, sexual thallus [3]
dark patches: male gametes
light patches: female gametes

Prasiola stipiata, attachment structure [3]

Chlorellales

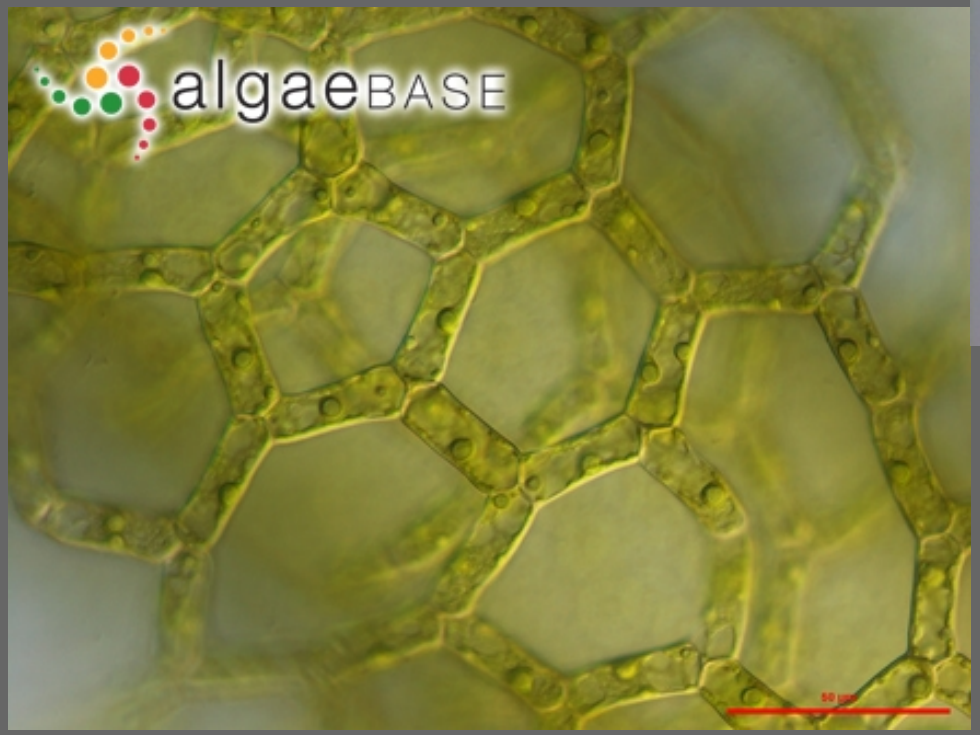
- unicellular or coenobial
- non-motile
- firm cell wall
- freshwater habitats
- isogamous, anisogamous, oogamous
- some species (*Chlorella*) researched as food source



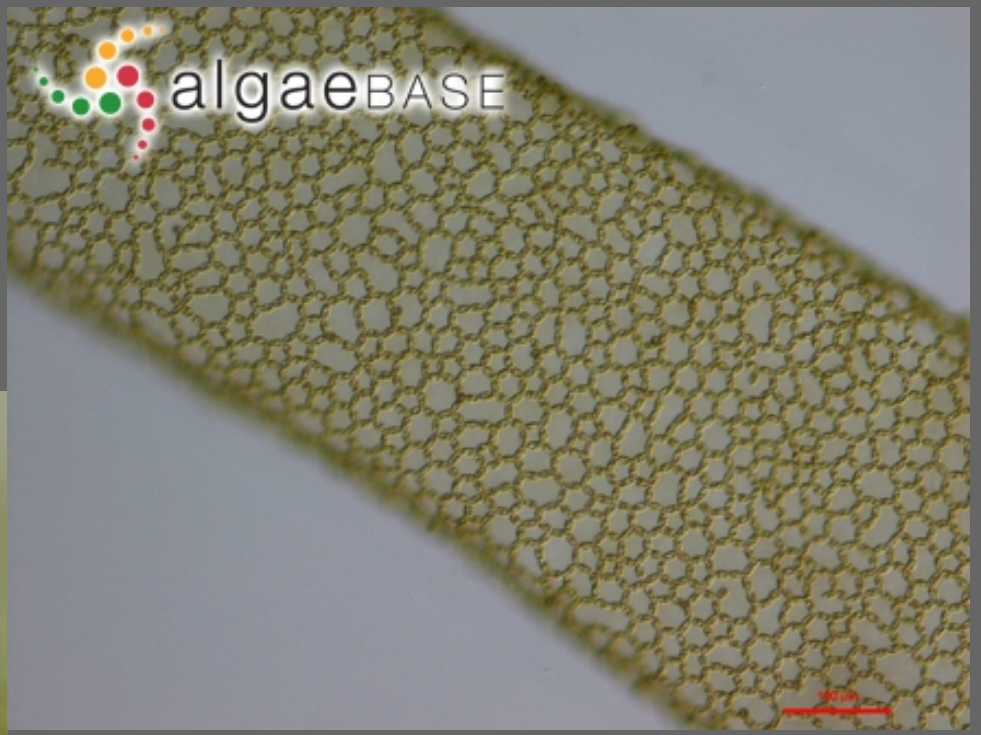
Chlorella vulgaris [3]

Chlorellales II

Hydrodictyon reticulatum
- 'water net'
- forms net-like colonies



Hydrodictyon reticulatum [3]

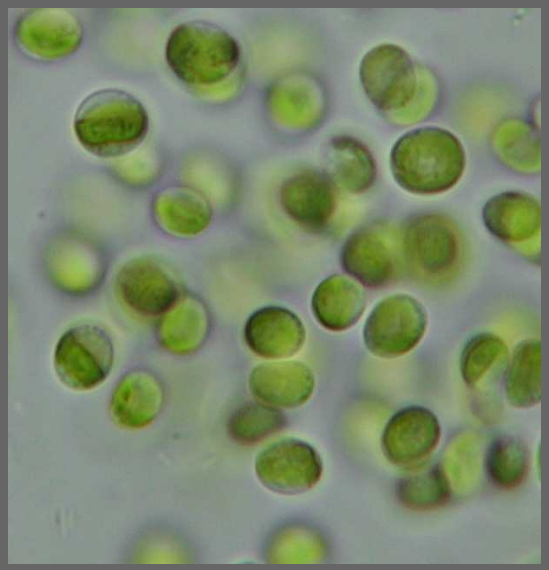


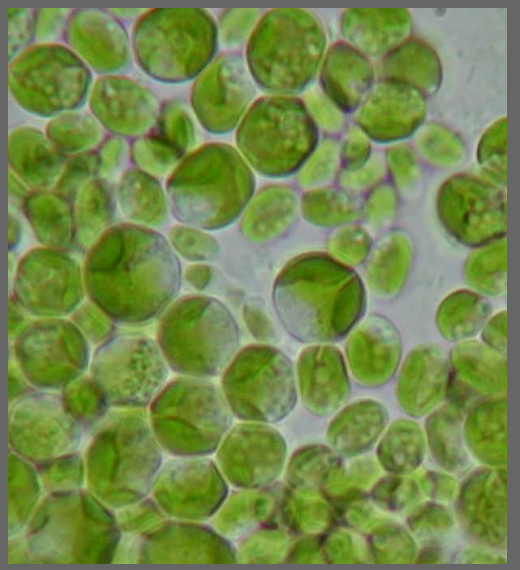
Hydrodictyon reticulatum [3]

Trebouxiales

- mostly symbiontic as phycobionts of lichens
- isogamous, anisogamous
- produce sugar alcohols (Ribitol)

Umbilicaria hirsuata [12]

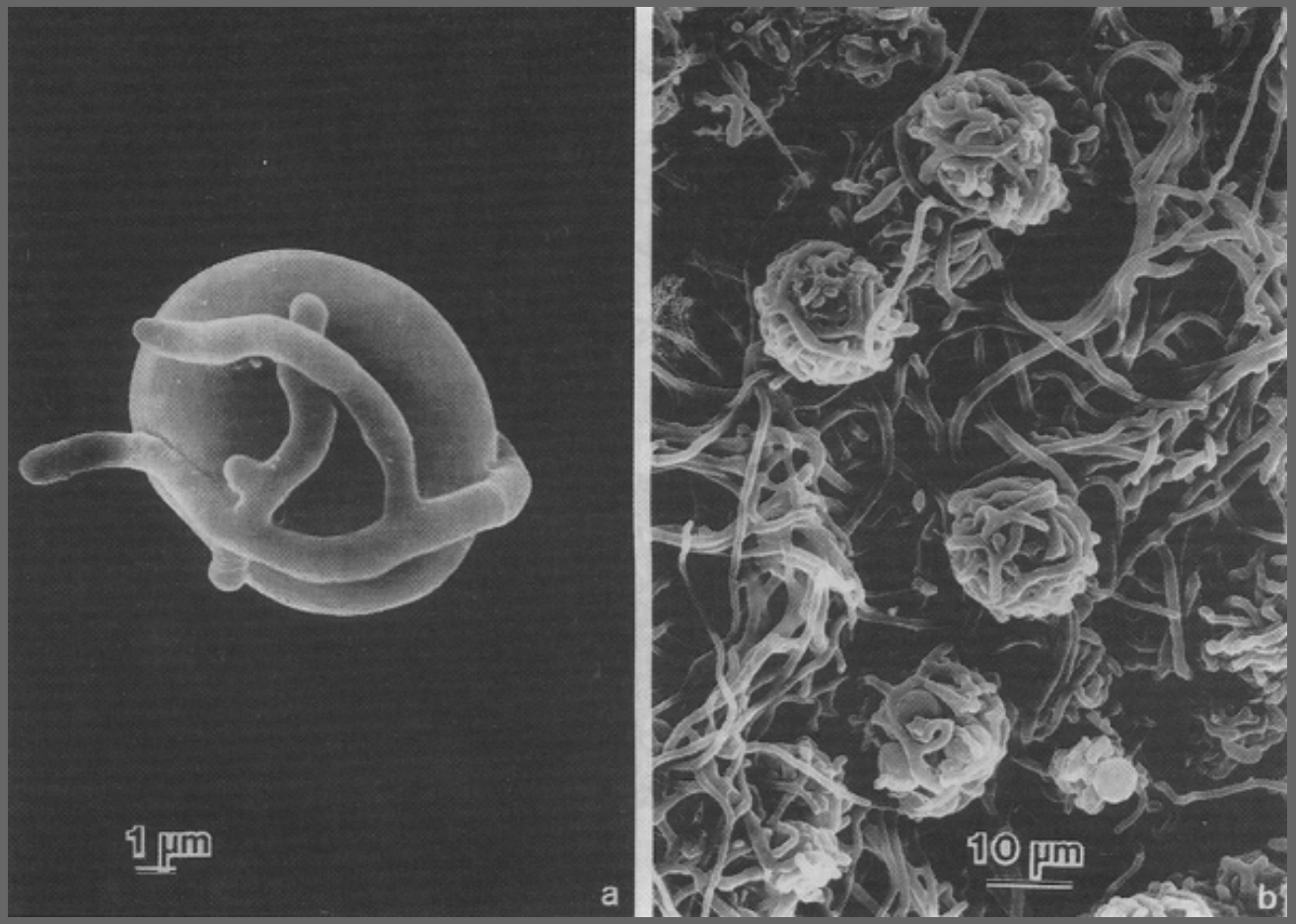




Trebouxia sp.

left: zoospores, center: vegetative cells, right: mature cells [13]

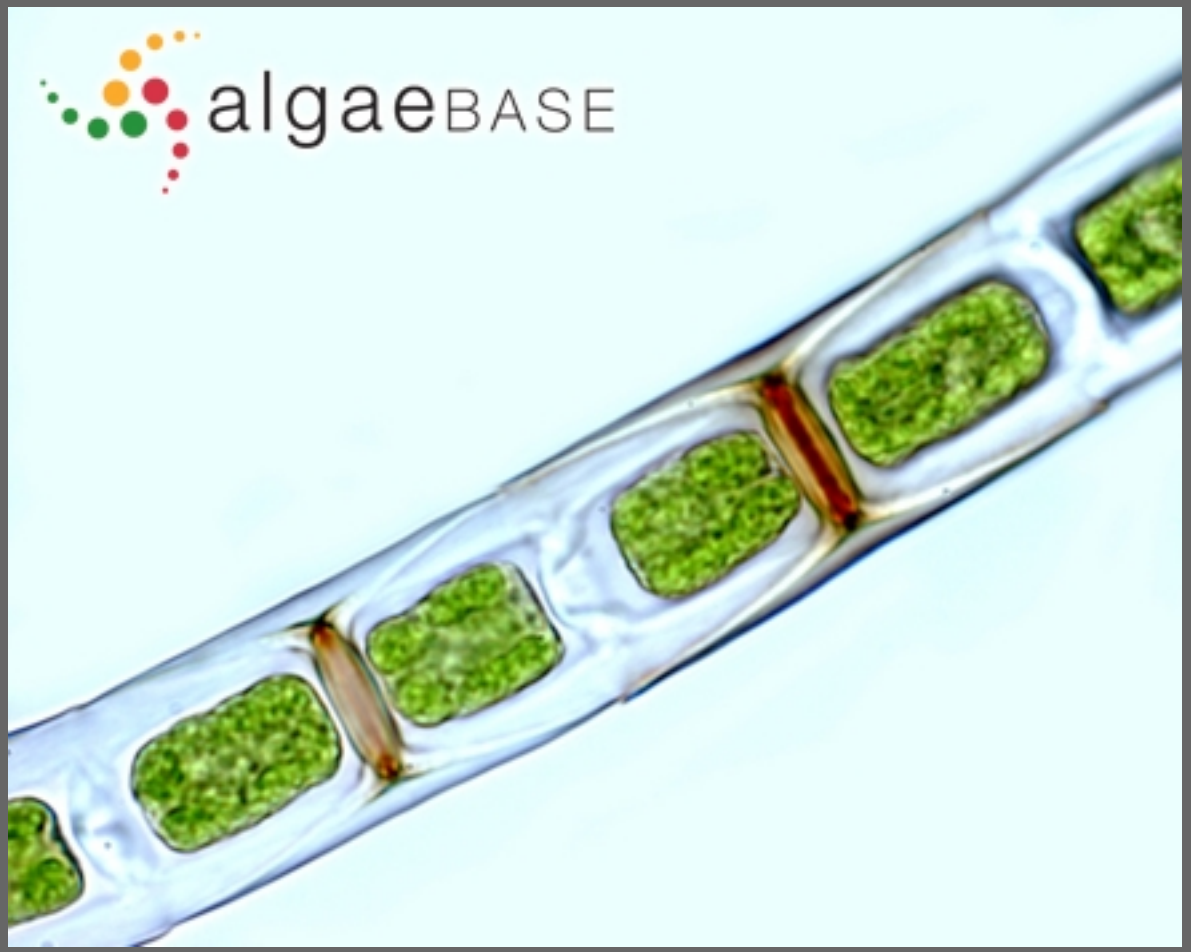
Trebouxiales II



envelopment of phycobiont *Trebouxia erici*
by hyphae of mycobiont *Cladonia cristatella*,
scanning electron micrographs [2]

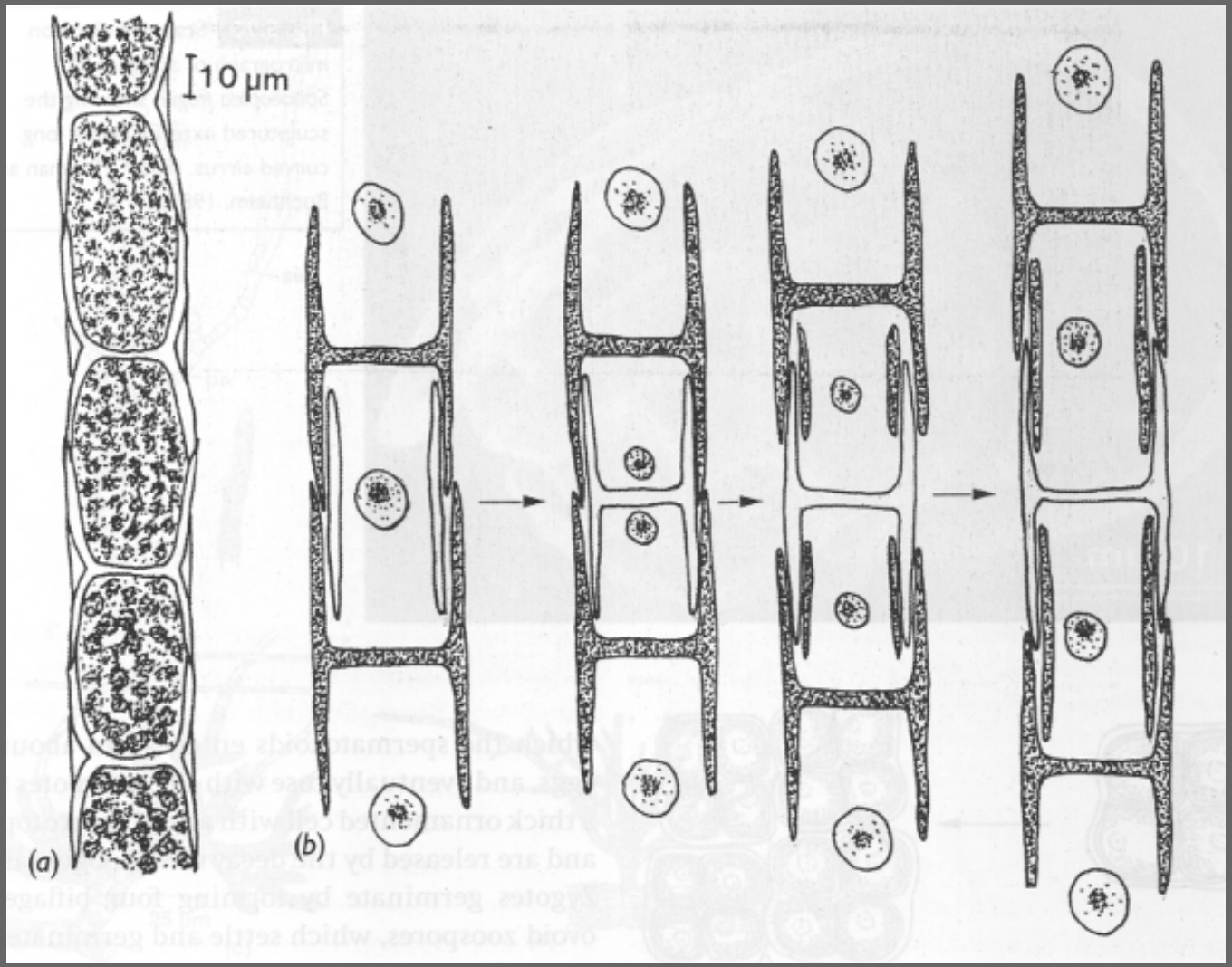
Sphaeropleales

- multinucleate
- H-shaped cell walls
- freshwater habitats
- oogamous
- unbranched filaments



Microspora amoena [3]

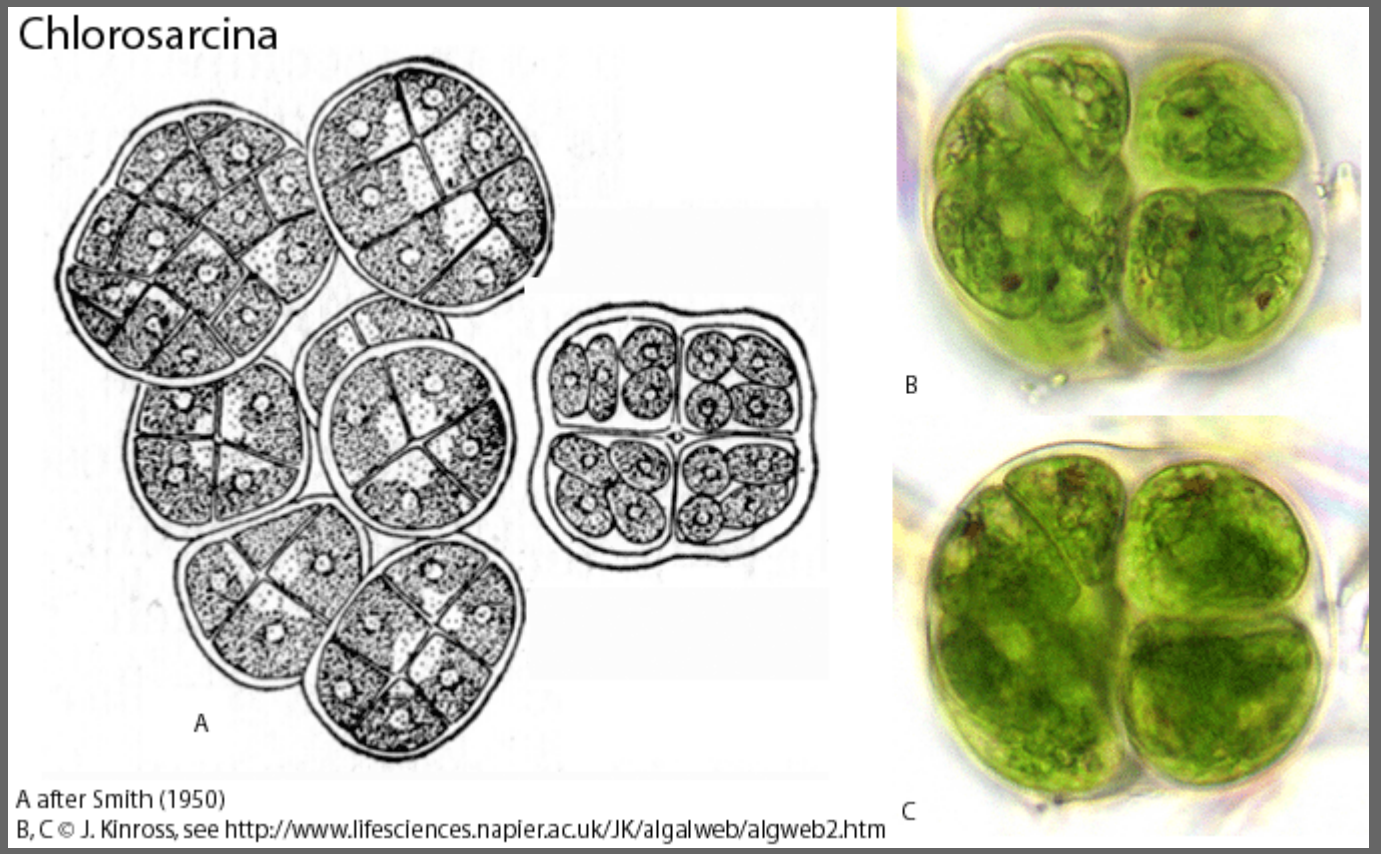
Sphaeropleales II



cell division in Microspora crassior [2]

Chlorosarcinales

- desmoschisis
- no plasmodesmata
- terrestrial, epiphytic habitats



Chlorosarcina sp. [14]

Chaetophorales

- uninucleate
- multicellular
- plasmodesmata
- heterotrichy
  prostrate & erect filaments
- filamentous

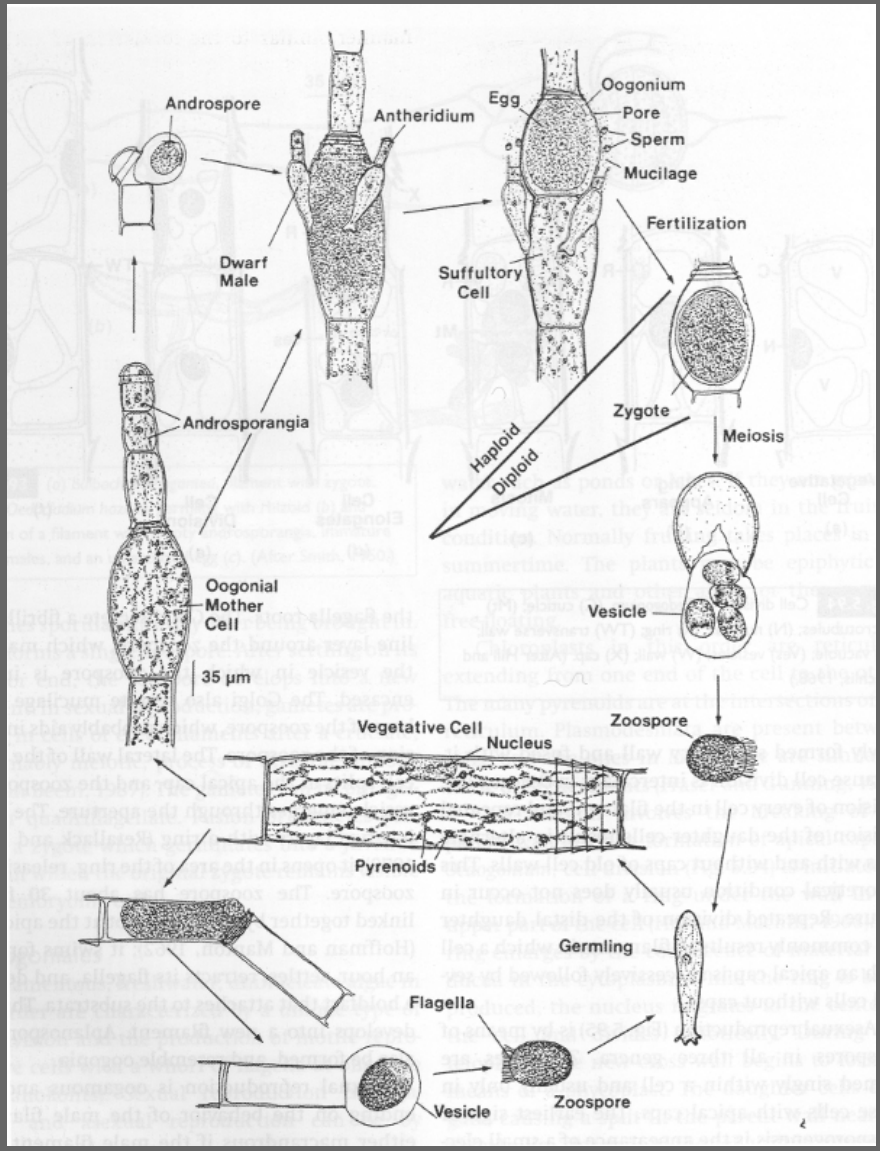
Draparnaldia plumosa [3]

Oedogoniales

- uninucleate
- multicellular
- plasmodesmata
- stephanokont
- oogamous
- special cell division
- nannandrous/macrandous species
- filamentous
- freshwater habitat

Oedogonium braunii [3]

Oedogoniales



life cycle of nannandrous species of *Oedogonium* [2]

Charophyceae

Morphology:

- zoids with 2 lateral flagella of unilateral type
- no rhizoplasts
- no eyespots

Molecular features:

- glycolate oxidase, urease
- cellulose synthase rosette

Habitat:

- freshwater, marine

Cell division:

- open mitosis
- persistent telophase spindle
- cytokinesis by cleavage furrow or phragmoplast

Reproduction:

- isogamous, anisogamous, oogamous
- formation of dormant zygotes

Orders of *Charophyceae*

- *Klebsormidiales*
- *Zygnematales*
  - *Zygnemataceae*
  - *Desmidiaceae*
  - *Mesotaeniaceae*
- *Coleochaetales*
- *Charales*

Klebsormidiales

- exogamous biflagellates
- no plasmodesmata
- freshwater & terrestrial habitats
- unbranched filaments

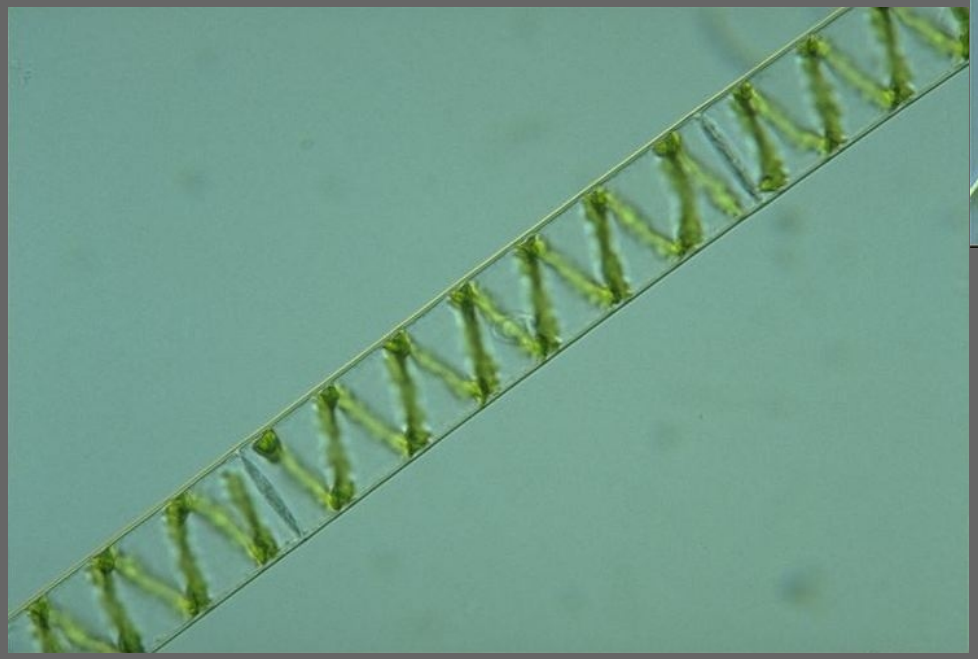
Klebsormidium flaccidum [3]

Klebsormidium flaccidum [3]

Zygnematales - Zygnemataceae

- multicellular
- unbranched filaments
- aplanogametes
- conjugation
- mostly freshwater habitats

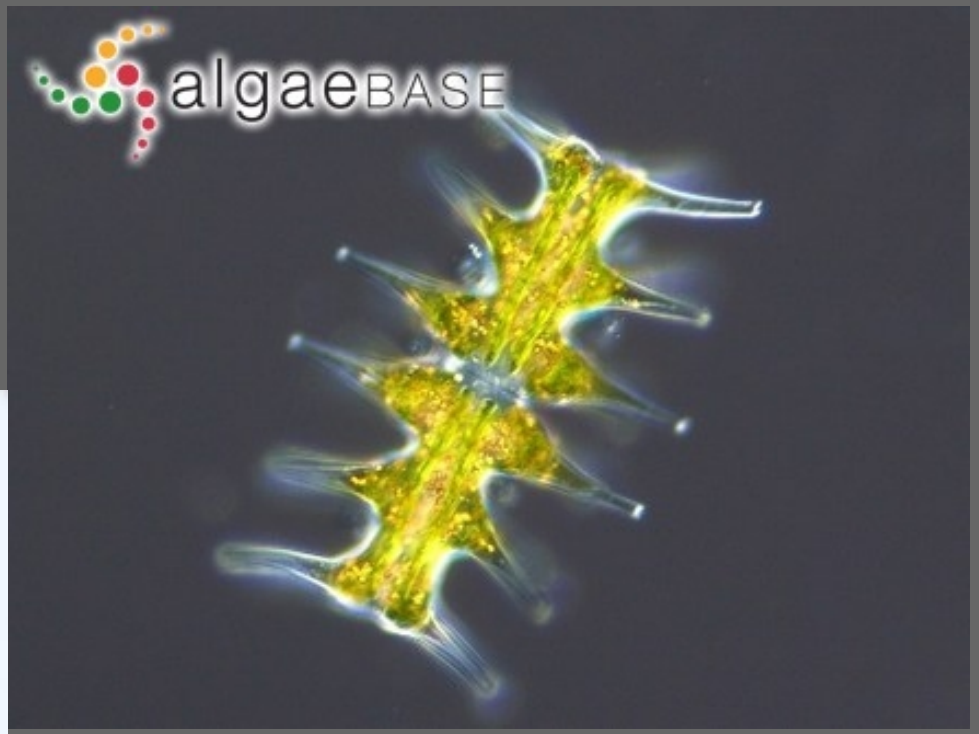
Spirogyra sp. [15]



Spirogyra porticales [15]

Zygnematales - Desmidiaceae

- unicellular, filaments, colonies
- semicells
- polymorphism
- conjugation
- freshwater habitats of low pH

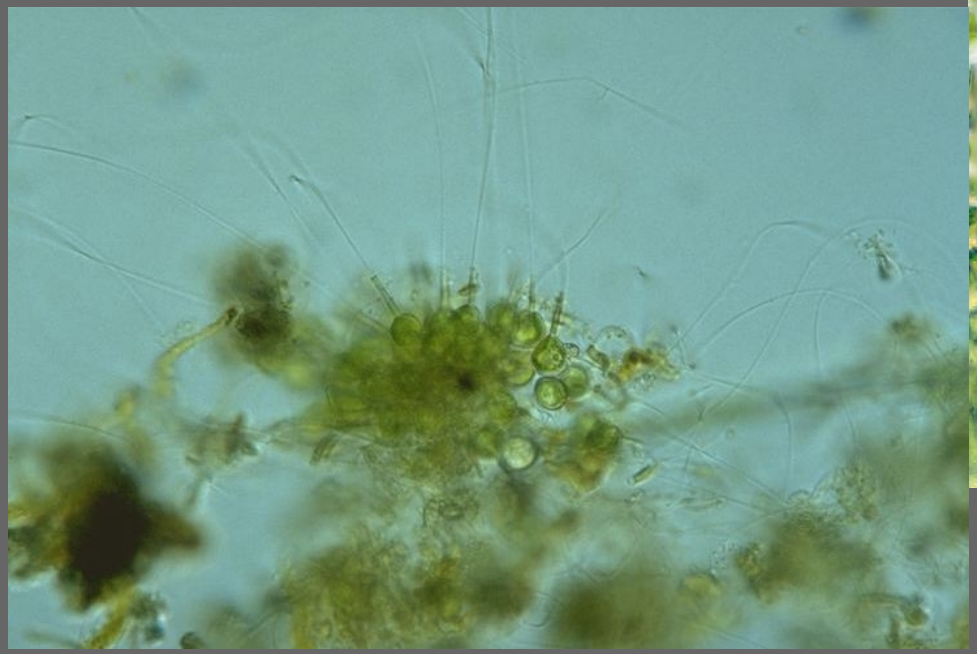


Micrasterias muricata [3]

Micrasterias oscitans [3]

Coleochaetales

- sheathed setae
- branched filaments
- pseudoparenchymatous disk
- oogamous
- trichogyne & spermocarp
- freshwater habitats



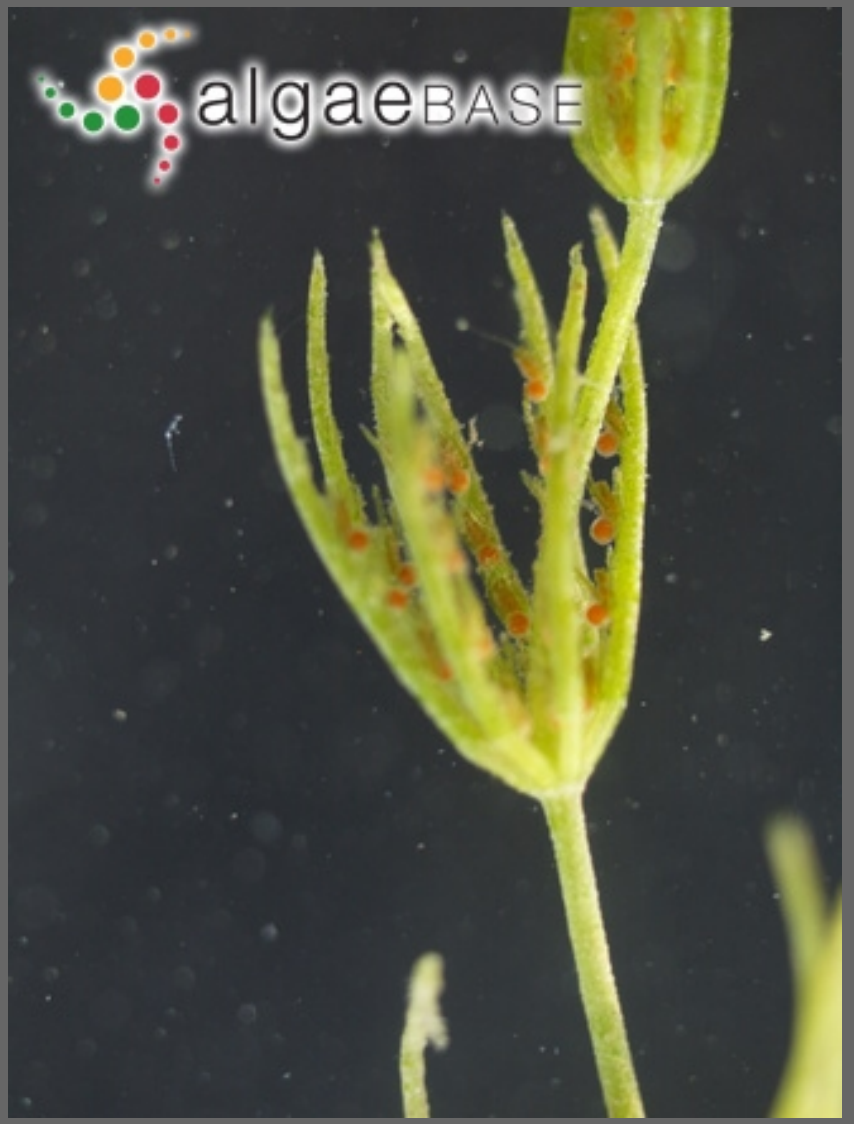
Chaetosphaeridium sp. [15]

Coleochaete conchata [16]

Charales

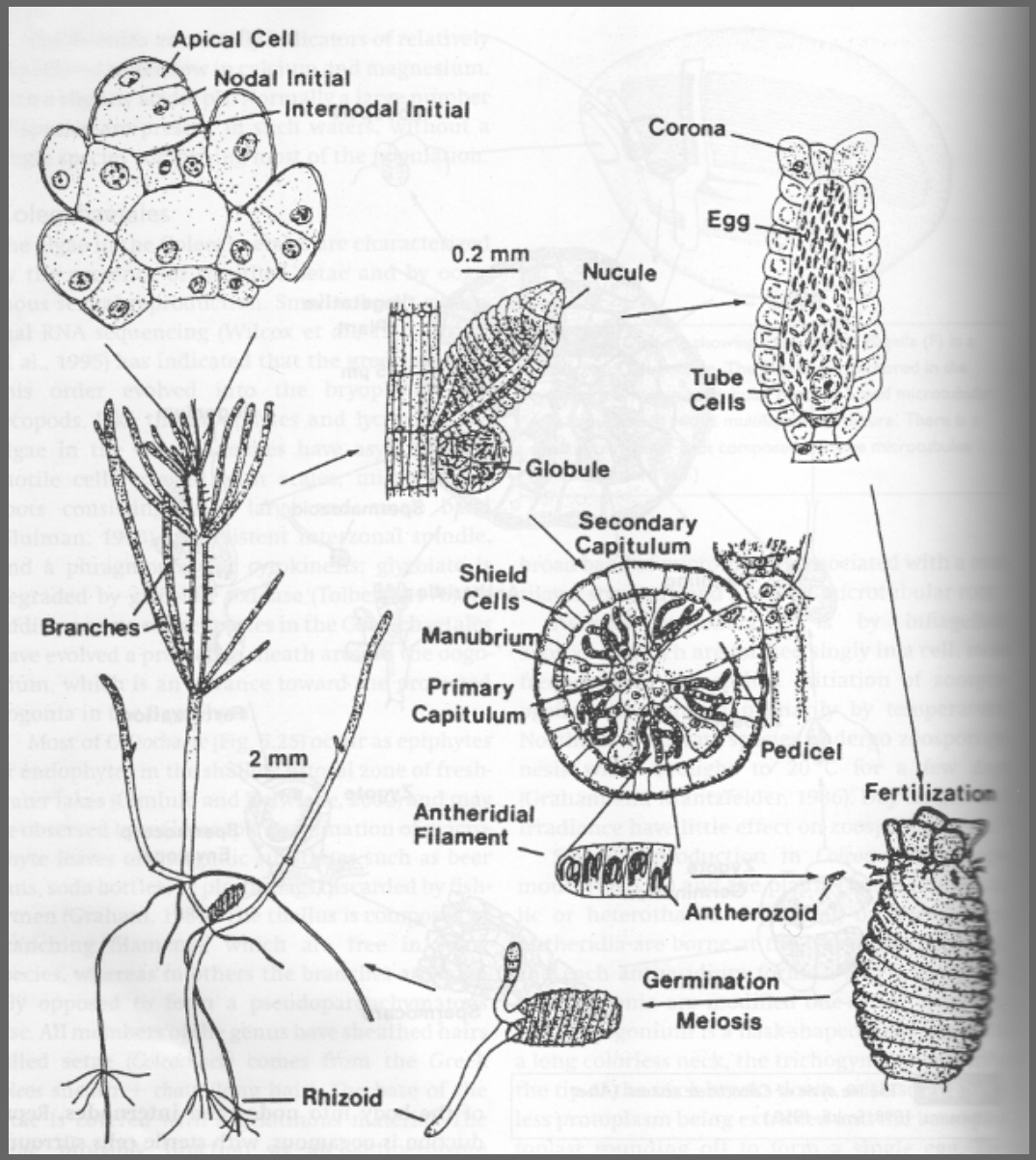
- nodes & internodes
- often calcified (stoneworts)
- no zoospores
- oogamous (globules & nucules)
- sterile cells around globules & nucules
- mostly freshwater habitats

Chara baltica [3]



Chara globularis [3]

Charales II



life cycle of *Chara* [2]

Green Algae of the Baltic Sea

- *Enteromorpha*
- *Monostroma*
- *Cladophora*
- *Chara*

Enteromorpha intestinalis

Enteromorpha intestinalis
(Linné, 1753) Link, 1820

german: Gemeiner Darmtang
color: yellowish to light green
height:
habitus: unbranched,
tubeformed lobes
habitat: thrives in shallow waters
on solid ground
distribution: Baltic Sea,
North Sea,
Atlantic Ocean,
Mediterranean Sea

Enteromorpha intestinalis [17]

Enteromorpha linza

Enteromorpha linza
(Linné, 1753) J.G. Agardh, 1883

german: Gewellter Darmtang
color: light to dark green
height: 10 – 50 cm
habitus: wavy edges
habitat: thrives in tidal zones
distribution: Baltic Sea,
North Sea,
Atlantic Ocean,
Mediterranean Sea

Enteromorpha linza [17]

Monostroma grivellei

Monostroma grivellei
(Thuret) Wittrock, 1866

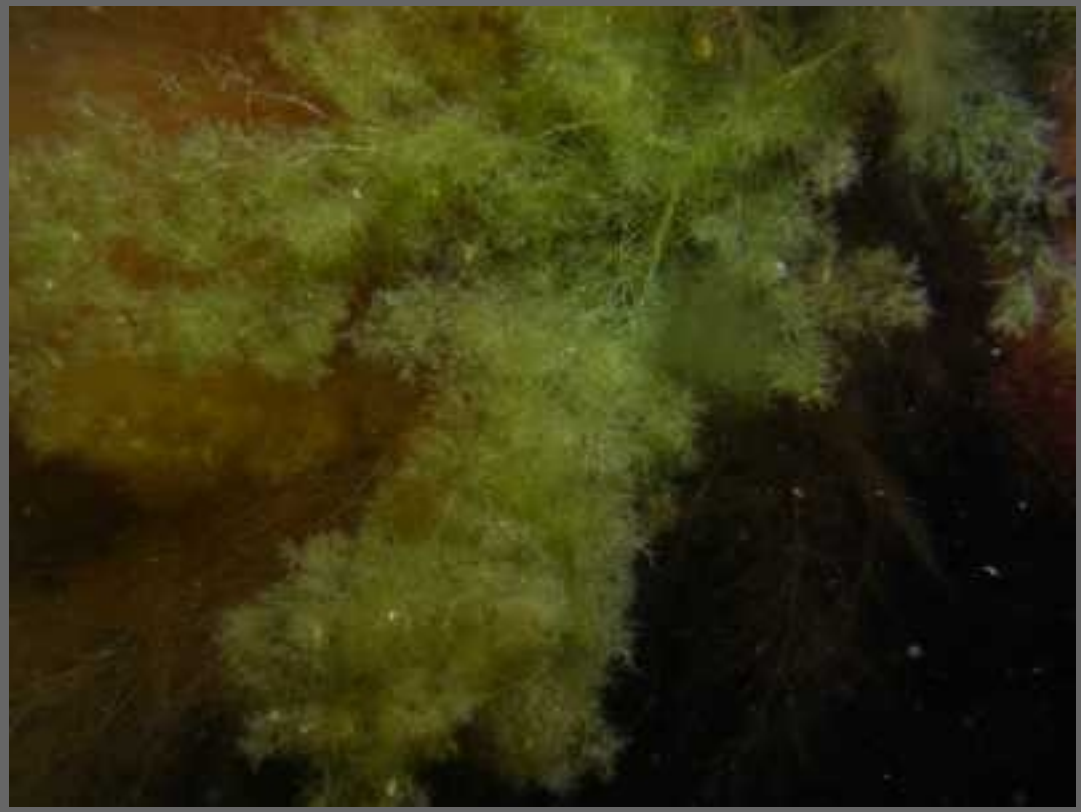
german: Trompetenalge
color: green
height: up to 20 cm
habitus: fragile leaves
habitat: thrives on stones and shells, February to May
distribution: Baltic Sea, North Sea

Monostroma grivellei [17]

Cladophora glomerata

Cladophora glomerata
(Linné) Kützing, 1843

german: Büschel-Zweigfadenalge
color: light to dark green
height: 5 - 25 cm
habitus: bushy edges
habitat:
distribution: Baltic Sea with up to 15 ‰ salt, freshwater



Cladophora glomerata [17]

Cladophora rupestris

Cladophora rupestris
(Linné) Kützing, 1843

german: Felsen-Zweigfadenalge
color: dark green
height: 5 – 25 cm
habitus: branched, bushy
habitat: thrives in shallow water
on stones
up to 25 m depth,
perennial
distribution: Baltic Sea,
North Sea

Cladophora rupestris [17]

Chara aspera

Chara aspera
Willdenow 1809
Rough Stonewort

german: Rauhe Armleuchteralge
color: greenish-brownish
height: 3 -15 cm
habitus: calcified, branched,
stems longitudinally
striated with small thorns
habitat: thrives in shallow,
calm waters up to 1.5 m depth
distribution: Baltic Sea, North Sea,
lime rich freshwater,
most prevalent *Chara*
species in the Baltic Sea

Chara aspera, male plant
with orange coloured antheridia
Vitter Bodden, 0.5 m water depth [18]

Chara baltica

Chara baltica
Bruzelius 1824
Baltic Stonewort

german: Baltische Armleuchteralge
color: dark green color
height: 5 - 50 cm
habitus: weakly calcified, branched, stem with small thorns
habitat: thrives in calm waters from 0.5 to 1.5 m depth on stones and in sand
distribution: Baltic Sea, rare in North Sea, freshwater

Chara baltica, light coloured oogonia, orange coloured antheridia
Vitter Bodden, 0.5 m water depth [18]

Chara canescens

Chara canescens,
Loiseleur-Deslongchamps 1810
Bearded Stonewort

german: Brackwasser Armleuchteralge
color: dark green
height: 3 - 30 cm
habitus: not calcified, branched,
brush-like appearance,
stem densly covered
with long thorns,
6 -10 nodes of 1.5 cm length
habitat: thrives in calm waters
from 0.5 to 1.5 m depth
on stones, rocks and in sand
distribution: Baltic Sea, freshwater,
brackish waters of North Sea

Chara canescens, female plant
with light coloured oogonia
Vitter Bodden, 0.5 m water depth [18]

Chara horrida

Chara horrida
Wahlst 1862

german:
color:
height:
habitus:
habitat: thrives in calm waters from 0.5 to 3 m depth on soft ground
distribution: rare, Baltic Sea, mainly south and middle Sweden, disappeared from German locations, North Sea

Chara horrida [19]

References:

- van den Hoek, Mann, Jahns; *Algae: an introduction to phycology;* 1st ed.; Cambridge University Press 1995

- Lee; *Phycology;* 4th ed.; Cambridge University Press 2008

Images:

[1]: van den Hoek, Mann, Jahns; *Algae: an introduction to phycology;* 1st ed.; Cambridge University Press 1995
[2]: Lee; *Phycology;* 4th ed.; Cambridge University Press 2008
[3]: www.algaebase.org
[4]: starcentral.mbl.edu Marine Biological Laboratory, Woods Hole, Massachusetts, USA
[5]: Wikipedia DE
[6]: Protist Image Data Evolutionary & Integrative Genomics, Université de Montréal, Canada
[7]: Convoluta Alfred Hauck, Universität Heidelberg, Germany
[8]: Snowalgae Nozomu Takeuchi, Dept. of Earth Sciences, Chiba University, Japan
[9]: Chlamydomonas nivalis Chris Impey, *The Living Cosmos*
[10]: Aquacarotene Inc. Australia
[11]: The MAGIC is BAC Roland Thomas, *The MAGIC is BAC*
[12]: Umbilicaria hirsuata Buday Ádám, Hungary
[13]: Lichens Dept. Plant Physiol. and Anatomy, Masaryk University, Czech Republic
[14]: Plant Diversity Research Department of Environment, Climate Change and Water NSW, Botanic Gardens Trust, Sydney, Australia
[15]: Taxonomy Chlorophyta Hosei University, Tokyo, Japan
[16]: The Charophyceae University of Maryland, College of Chemical and Life Sciences, USA
[17]: Unterwasser Welt Ostsee Peter Jonas, Hamburg, Germany
[18]: Videogalerie Institut für Ökologie, Universität Greifswald, Germany
[19]: Helsinki Commission Baltic Marine Environment Protection Commission, Finland
[20]: Description of the Green Algae Susquehanna University, Pennsylvania, USA
[21]: Tom Linder, IZMB, University of Bonn

Thanks for listening!

Leaf bug from Borneo, image © by Bill and Claire Leimbach