Discipline Courses-I
Semester-I
Paper: Phycology and Microbiology
Unit-VII
Lesson: Chlorophyceae – Cell structure; pigment composition & Evolutionary significance of *Prochloron*

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Chapter: Chlorophyceae

Cell Structure in Chlorophyceae

Members of Chlorophyceae are **eukaryotic** algae with an organised (membrane enclosed) cell nucleus containing DNA and organised plastids (chloroplasts) and all the cell organelles such as mitochondria, Golgi bodies, endoplasmic reticulum, and true vesicles. The protoplast is bounded by a thin and semipermeable plasma membrane and the cytoplasm possesses vacuoles. The streaming movements in the cytoplasm are of frequent occurrence.

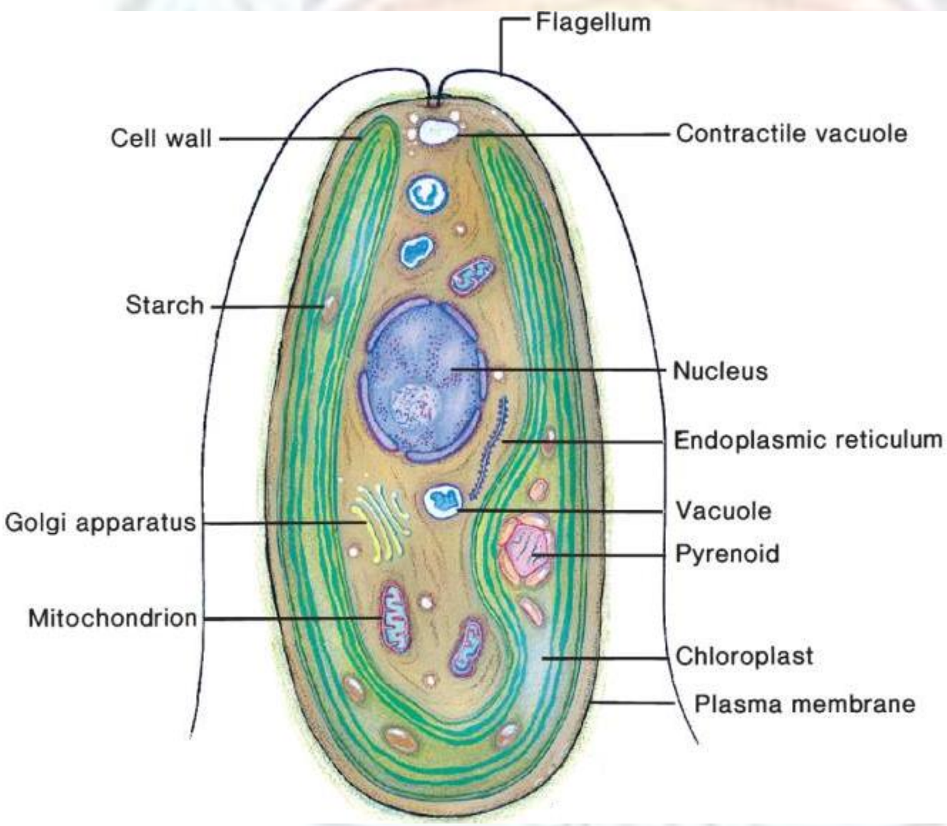


Figure: Diagrammatic sketch of a chlorophycean cell showing ultrastructural details.

Source: http://classroom.sdmesa.edu/eschmid/Lecture11-Microbio.htm

After studying this unit you will learn:

- The structure and composition of cell wall in Chlorophyceae.

- What are the various cellular organelles present in Chlorophyceae?
- Structure of chloroplast and the variations in shape of the chloroplast within Chlorophyceae.
- Structure and function of pyrenoid and eyespot.
- What are the various photosynthesizing pigments present in Chlorophyceae?
- Pigment composition, ultrastructure and the evolutionary significance of *Prochloron*
- How do the chlorophycean algae divide?
- Certain distinguishing biochemical features of Chlorophyceae.

What is the structure and composition of cell wall?

Except naked flagellates, zoospores and gametes, in most members of Chlorophyceae the cytoplasm is bounded by a definite cell wall. Cell walls usually have **cellulose** as the main structural polysaccharide, although xylans and mannans often replace cellulose in the some members. The submicroscopic morphology of the cell wall shows a fibrillar structure composed of 30-200 A wide cellulose microfibrills embedded in a smooth or slightly granular matrix. The microfibrils composed of cellulose are either laid down in two layers at right angles to each other (as shown in the ultramicrograph of a green algal cell) or in three layers, the third layer running in an obtuse angle to the other two. Algae in Chlamydomonadales have walls composed of glycoproteins (Goodenough and Heuser, 1985).

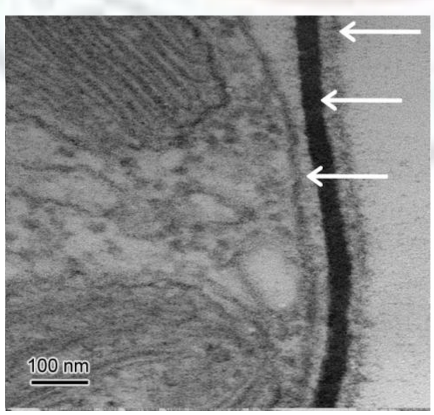


Figure: Two layers of the cell wall in Chlorophyceae (represented by arrowheads, the third arrow points towards the plasmalemma) Inner layer appears more electron dense than the outermost layer.

Source: Author

What is the nature and composition of mucilages?

Algal mucilages are mainly constituents of the continuous amorphous phase of cell walls. Mucilages have been examined from a number of genera in Chlorophyceae. Polysaccharides containing rhamnose, galactan sulphate and uronic acid have been isolated. Some mucilages have highly branched polysaccharides found to yield galactose, mannose and arabinose on hydrolysis.

Flagella

In Chlorophyceae, the motility of cells is due to small protoplasmic whiplike threads called flagella. They function as locomotory structure of the cell. The number of flagella varies from one to four to many. Flagella are of equal length and are inserted at the anterior or apical end of the motile cells. The flagella have a smooth surface and hence are of **whiplash type**. Usually there is a single granule at the base of each flagellum. It is known as **basal body** or blepharoplast. Each flagellum consists of a thin axial filament of **axoneme** surrounded by a cytoplasmic membrane or **sheath**. In a transverse or cross section the axoneme consists of 11 (9 peripheral+2 central) microtubules. Two of these are situated in the centre and are called **central tubules**. They are single, consisting of 13 protofilaments each and lie side by side. These central microtubules are surrounded by nine, **peripheral**, doublet microtubules arranged in a circle. Each peripheral doublet microtubule consists of A and B tubules: the A tubule is a complete microtubule with 13 protofilaments, whereas the B tubule have 11 protofilaments. All the peripheral doublet microtubules are surrounded by a common cytoplasmic sheath.

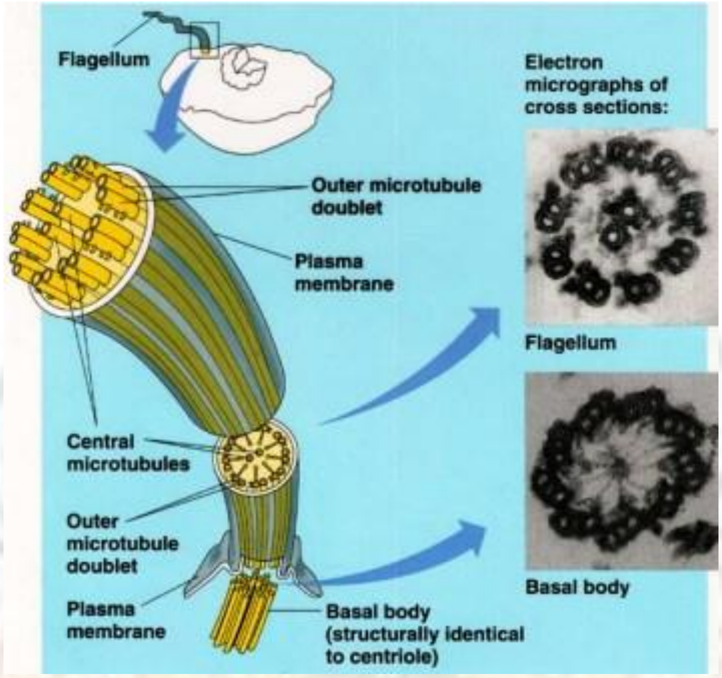


Figure: Eukaryotic 9+2 whiplash flagellum.

Source: http://comenius.susqu.edu/biol/202/animals/terms/whiplash-flagellum.htm

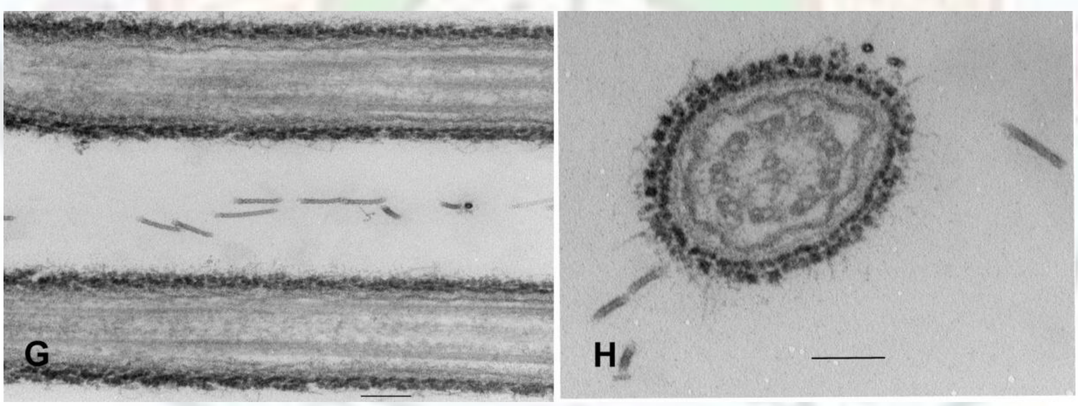


Figure: The longitudinal and a transverse section of flagella from a green alga, 9+2 arrangement of microtubules can be seen in the transverse section.

Source: Author: Arora M. *et al.,* 2013

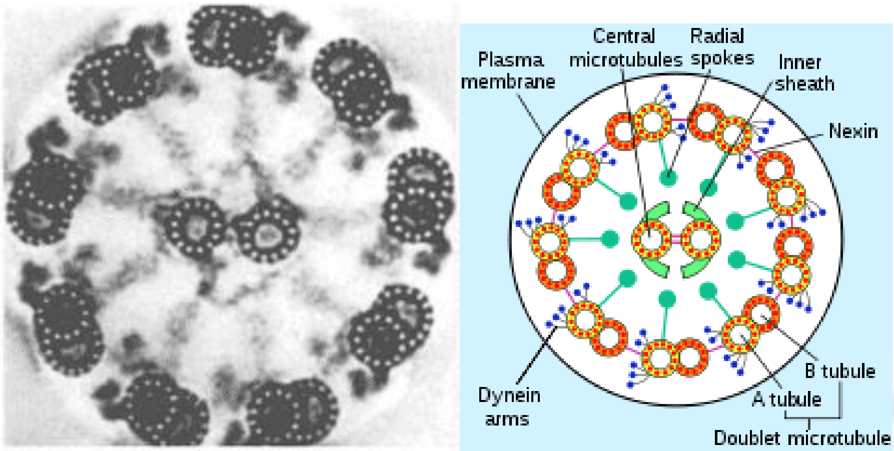


Figure: Labelled cross section of a flagellum

Source: http://en.wikipedia.org/wiki/Flagellum

Nature and organization of nucleus

Cells in Chlorophyceae have a well organized nucleus. The number of nuclei per cell varies. Both uninucleate and multinucleate cells have been reported in Chlorophyceae. In uninucleate algae nucleus usually lies alongside the cell wall but sometimes it is suspended in the centre of the cell by fine cytoplasmic threads (e.g., *Spirogyra*). Nuclear membrane is a double layered structure made up of proteins and lipids. The outer membrane is continuous with the membranes of endoplasmic reticulum. The two nuclear membranes are separated by a perinuclear space. Nuclear pores provide aqueous channels through the nuclear envelope and are composed of nucleoporin proteins. Each nucleus contains one or more pronounced nucleoli. Each nucleolus is made up of RNA and proteins

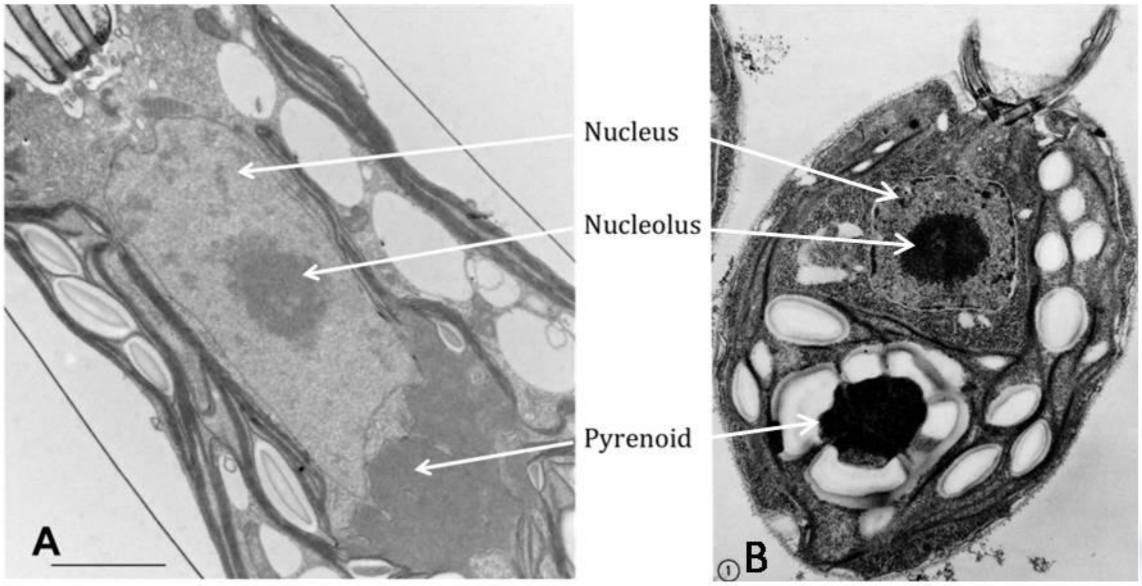


Figure: Ultramicrographs of green alga showing nucleus, nucleolus and pyrenoid

Source: **A** Author

B http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2107204/pdf/543.pdf

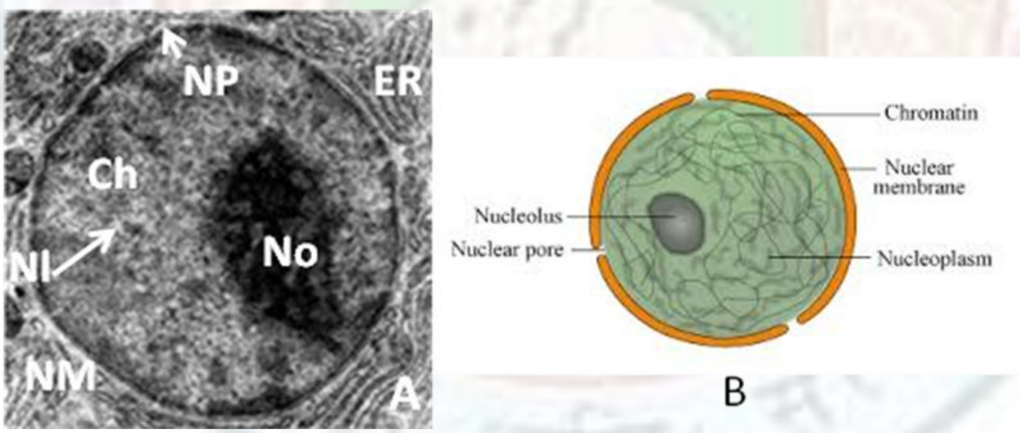


Figure: Nucelus **(A)** Micrograph No- nucleolus, NP- nuclear pore, NM- nuclear membrane, Nl-Nucleoplasm, Ch- Chromatin **(B)** Labelled diagram

Source:
http://www.wikipremed.com/image.php?img=040203_68zzzz269550_Micrograph_of_a_cell_nucleus_68.jpg&image_id=269550

Are Golgi bodies, Mitochondria, Endoplasmic reticulum and vacuoles present in chlorophyceae?

Mitochondria have been observed in members of Chlorophyceae. They are bounded by a double membrane, inner one projecting into the lumen in the form of many folds. They function as sites of enzyme action. In some members, the mitochondria have plate-like cristae which are long extensions of inner lamella.

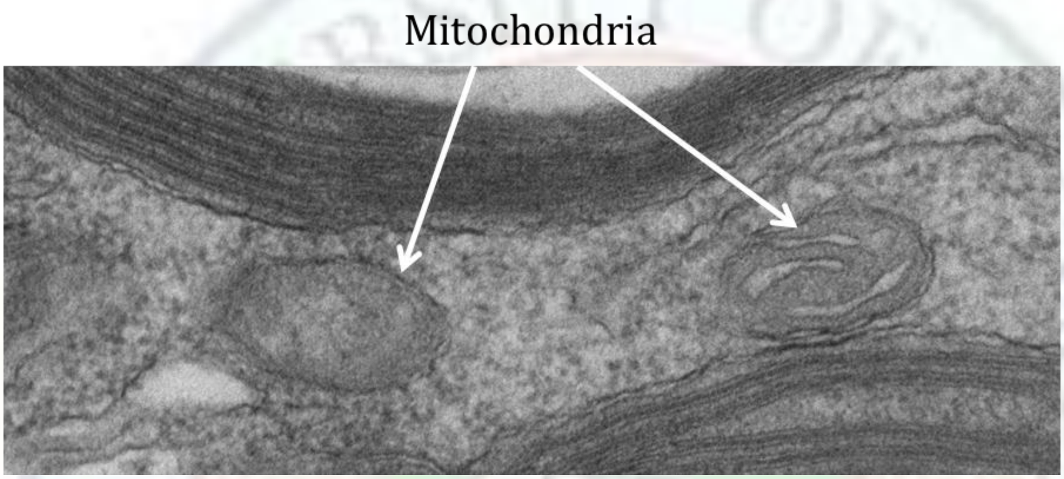


Figure: Mitochondria bounded by double membrane and the inner membrane is projecting into the lumen

Source: Author: Arora M. *et al.,* 2013

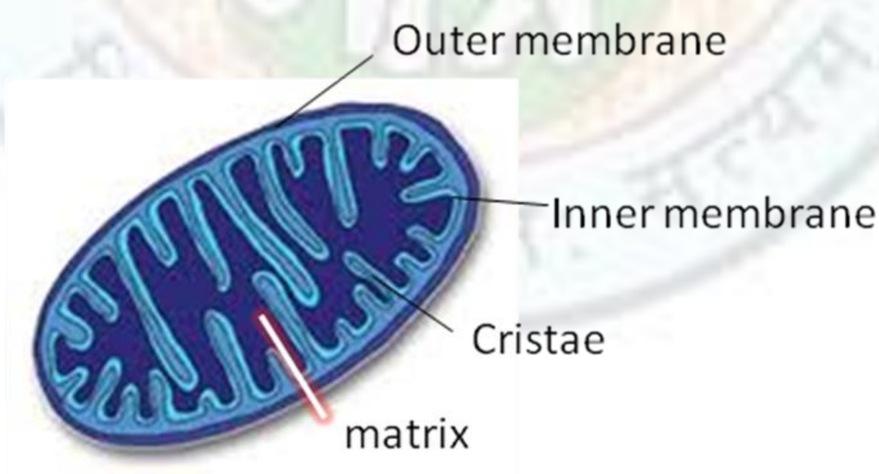


Figure: Diagrammatic representation of mitochondria

Source: Author

Golgi bodies or dictyosomes are encountered in a number of green algae. In *Chlamydomonas,* they are found in the region of the nucleus, whereas in some algae they are associated with the flagellar base. Golgi bodies are composed of stacks of flat vesicles. About 10-20 Golgi bodies can be seen in the cytoplasmic matrix without any apparent association with any particular organelle.

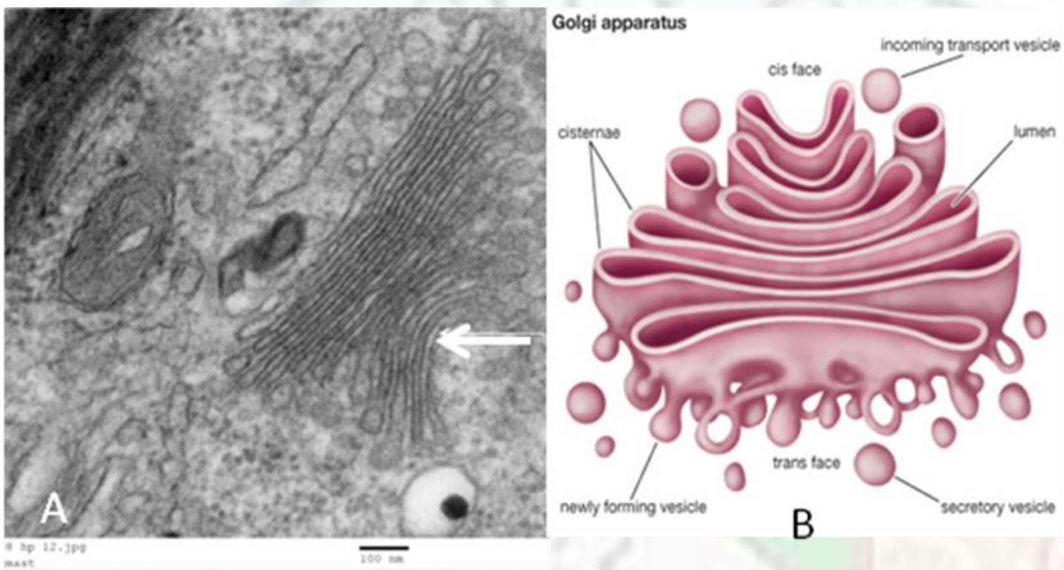


Figure: A Electron micrograph **B** Diagrammatic representation of Golgi bodies composed of stacked vesicles in a Chlorophycean algae

Source: A: Author

B:http://www.meritnation.com/ask-answer/question/draw-a-neat-labelled-diagram-of-golgi-apparatus/the-fundamental-unit-of-life/2451956

The endoplasmic reticulum (ER) of green algae traverses the ground substance of the cells. The ER in *Chlamydomonas* has various membranous elements and is concentrated mostly in the anterior half of the cell. The system does not penetrate either the chloroplast or the pyrenoid. The membrane of the ER is often studded with small particles (ribosomes).

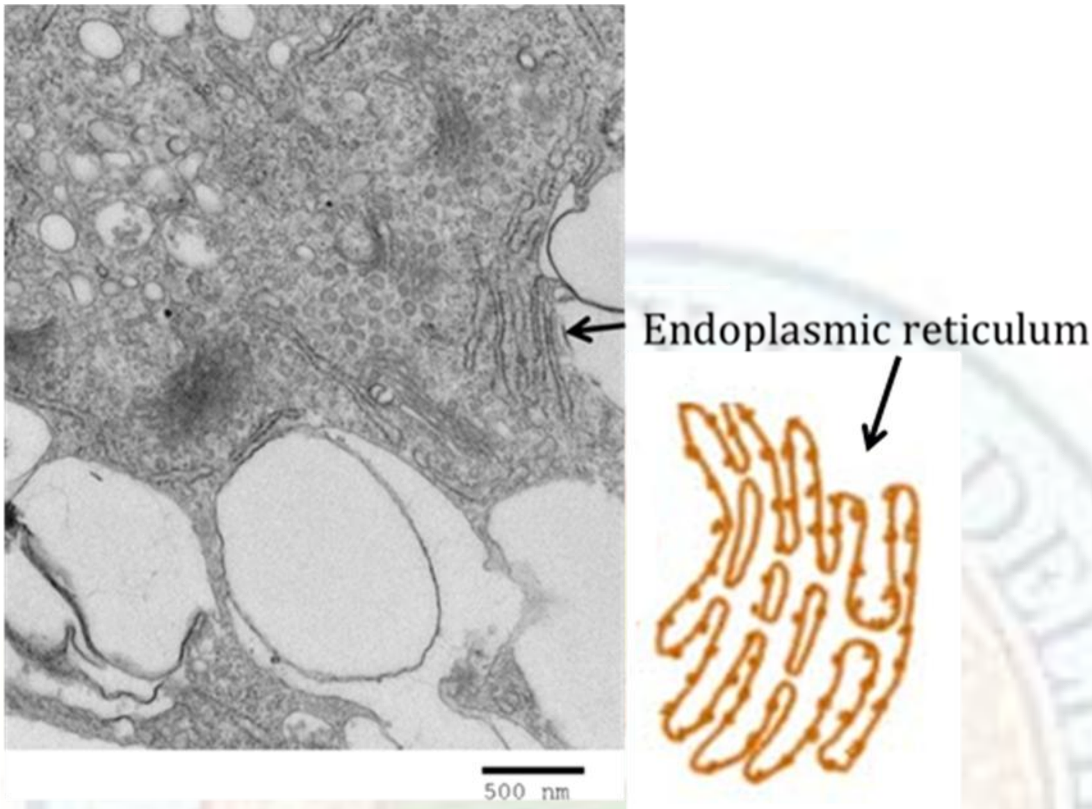


Figure: Endoplasmic reticulum traversing into the ground substance of algae

Source: Author

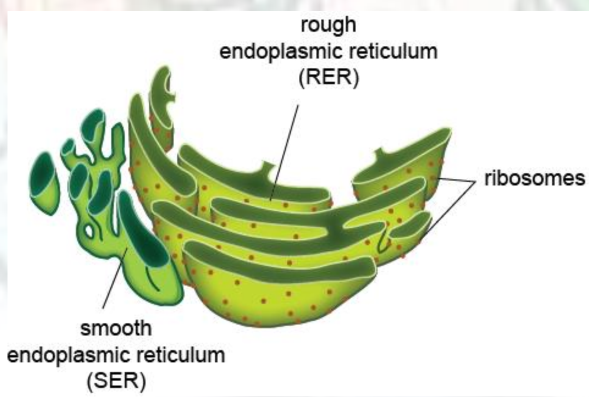


Figure: Endoplasmic reticulum

Source:http://www.shmoop.com/biology-cells/most-eukaryotic-cells.html

Mature cells of most of the Chlorophyceae possess one or more **vacuoles**. Each vacuole is bounded by a distinct membrane, called tonoplast. Some of the vacuoles may be **contractile** and are considered to be **excretory** in function. These vacuoles show periodic contractions and throw out the waste products of the cell.

What are Chloroplasts?

Chloroplasts are autonomous cytoplasmic bodies containing the complete cellular apparatus needed for photosynthesis. Each chloroplast is surrounded by a **double membrane system**. In all chloroplasts internal membrane system is embedded in a matrix called **stroma**. The internal membranes are actually closed, flattened sacs termed **thylakoids**. The thylakoids of green algae are much larger than those of higher plants. In green algae they are stacked in groups of 2, 3 or 4. Chloroplast consists of a matrix or stroma containing a number of small discs or thylakoids. The thylakoids contain all the chlorophyll pigment of the chloroplast and are made up of proteins and lipid substances. The stroma contains small **ribosomes** and osmiophillic globules.

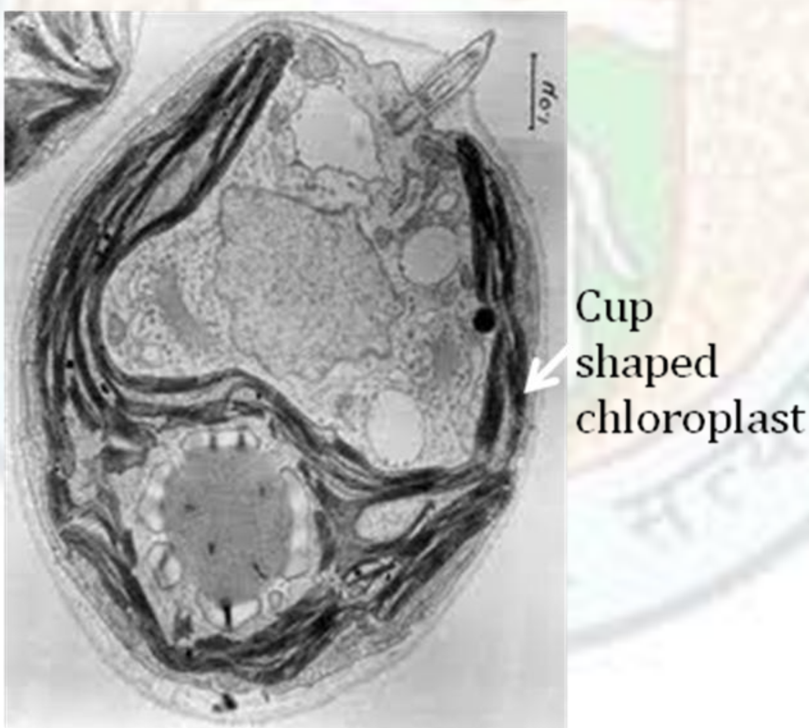


Figure: An electron micrograph showing a central longitudinal section of the unicellular green alga *Chlamydomonas reinhardtii*. The single cup shaped chloroplast with pyrenoid (storage granule) surrounds the central nucleus and other organelles

Source: http://www.cellimagelibrary.org/images/37252

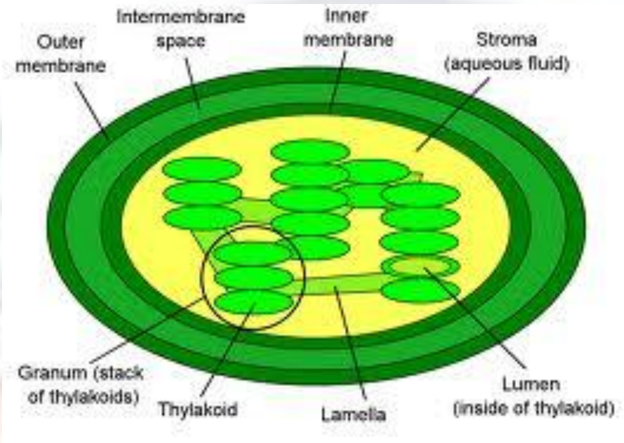


Figure: Chloroplast structure

Source: http://en.academic.ru/dic.nsf/enwiki/3526

Range of chloroplasts within chlorophyceae:

The shape of chloroplasts in Chlorophyceae shows wide variations. They are either axile (situated along the central axis of the cell) or parietal and can be grouped as follows:

Cup shaped: *Chlamydomonas, Chlorella*

Stellate (star shaped): *Cylindrocapsa involuta*

Laminate (in the form of a thin plate or sheet extending full cell length): *Ulothrix*

Reticulate (Mesh like network): *Oedogonium, Hydrodictyon*

Spiral (Chloroplast is ribbon shaped and spirally arranged): *Spirogyra*

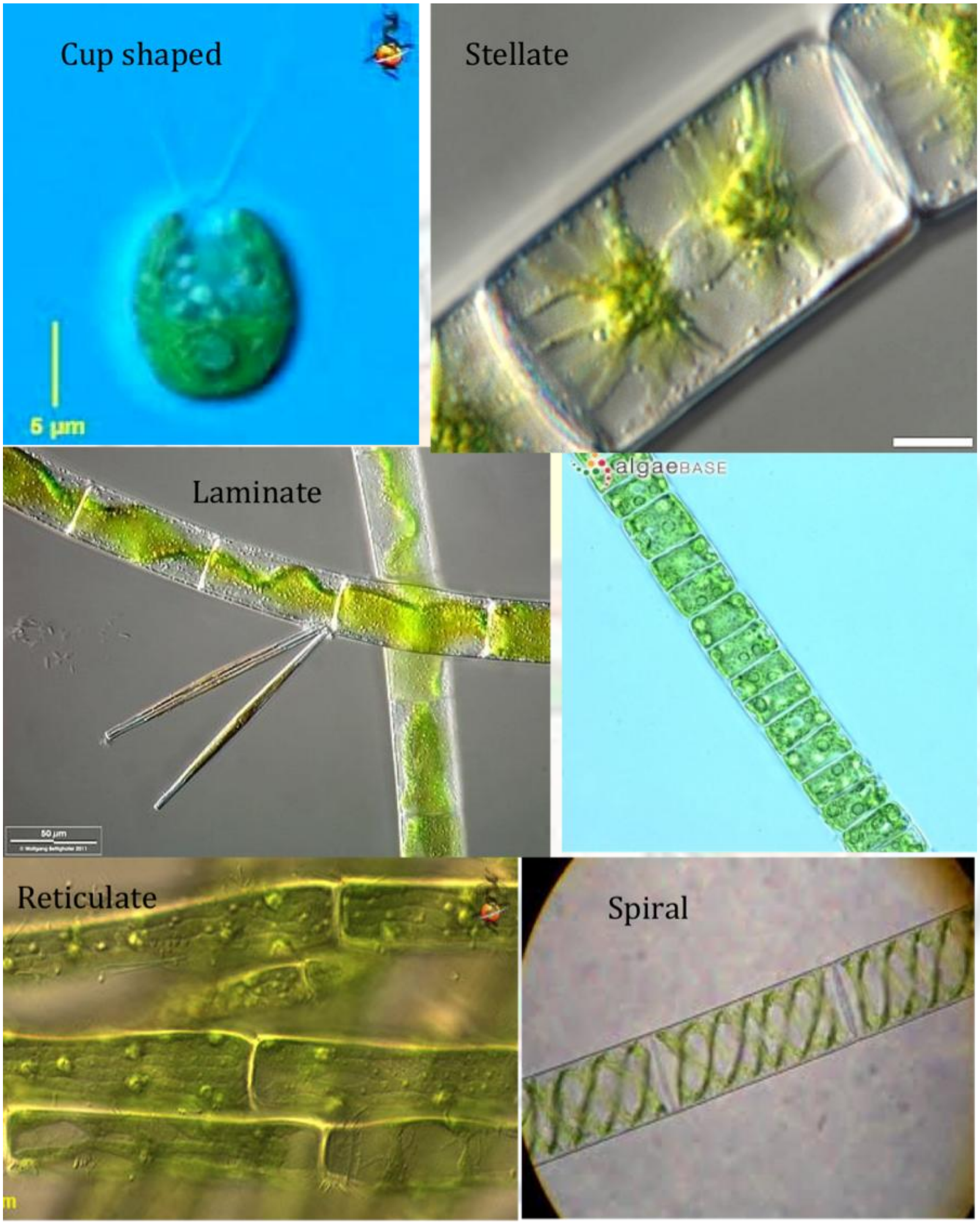


Figure: Variation in the shape of chloroplasts in Chlorophyceae

Source: http://eol.org/pages/11591/hierarchy_entries/34801995/overview; http://eol.org/pages/11680/overview;

http://planktonnet.awi.de/sci_images_detail.php?itemid=61337http://eol.org/data_objects/2091755;http://commons.wikimedia.org/wiki/File:Spirogyra.JPG

What are pyrenoids?

In green algae starch is formed within the chloroplasts, in association with one or more distinct, rounded, proteinaceous body called pyrenoid. Pyrenoid consists of a central granular core surrounded by tightly packed starch plates. Presence of starch grains within the chloroplast is a distinguishing feature of green algae. In some genera amyloplasts containing starch grains are present in the chloroplasts. Pyrenoids become reduced or diminish if the alga experience conditions of starvation and reappear once the conditions become favourable.

Pyrenoids are considered to be important components of the **carbon concentrating mechanism (CCM)** in algae. Pyrenoid is not a membrane-bound structure, though it has a definite physical outline and is usually surrounded by **starch cells** or starch plates. A large amount of enzyme **RuBisCO** (Ribulose-1, 5-bisphosphate carboxylase oxygenase) is located in the pyrenoid. In the pyrenoid CO_2 is **concentrated** around this RuBisCO, permitting the enzyme to work at a higher efficiency. Inflated tubule-like structures of the thylakoids that penetrate into the pyrenoid appear to be the path of CO_2 into the pyrenoid.

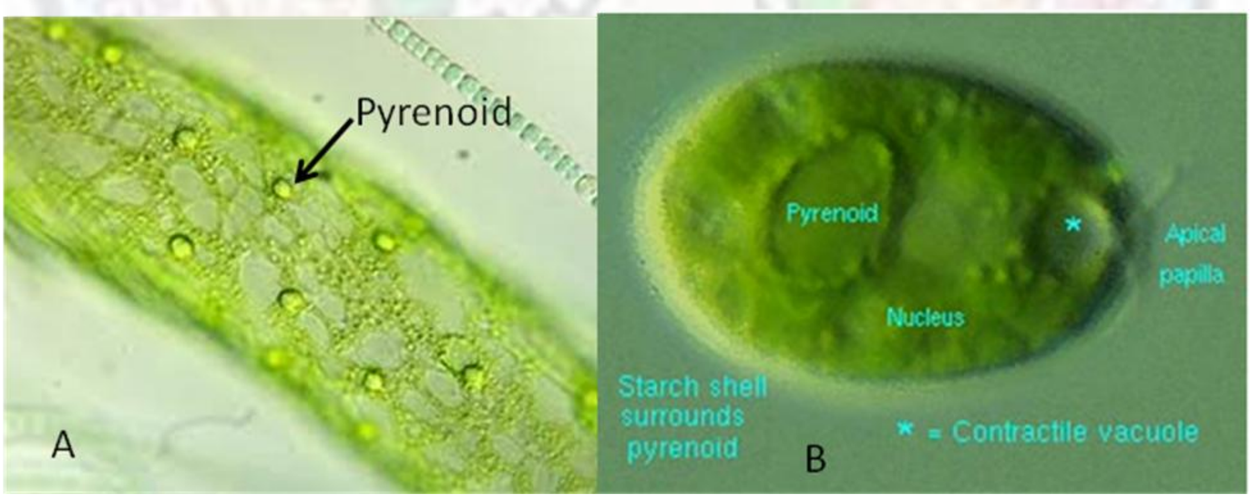


Figure: Pyrenoids in *Spirogyra* and *Chlamydomonas*

Source:
http://botit.botany.wisc.edu/Resources/Botany/Chlorophyta/Hydrodictyon/Chloroplast%20pyrenoids%20MC.jpg.html; http://www.jochemnet.de/fiu/bot4404/BOT4404_28.html

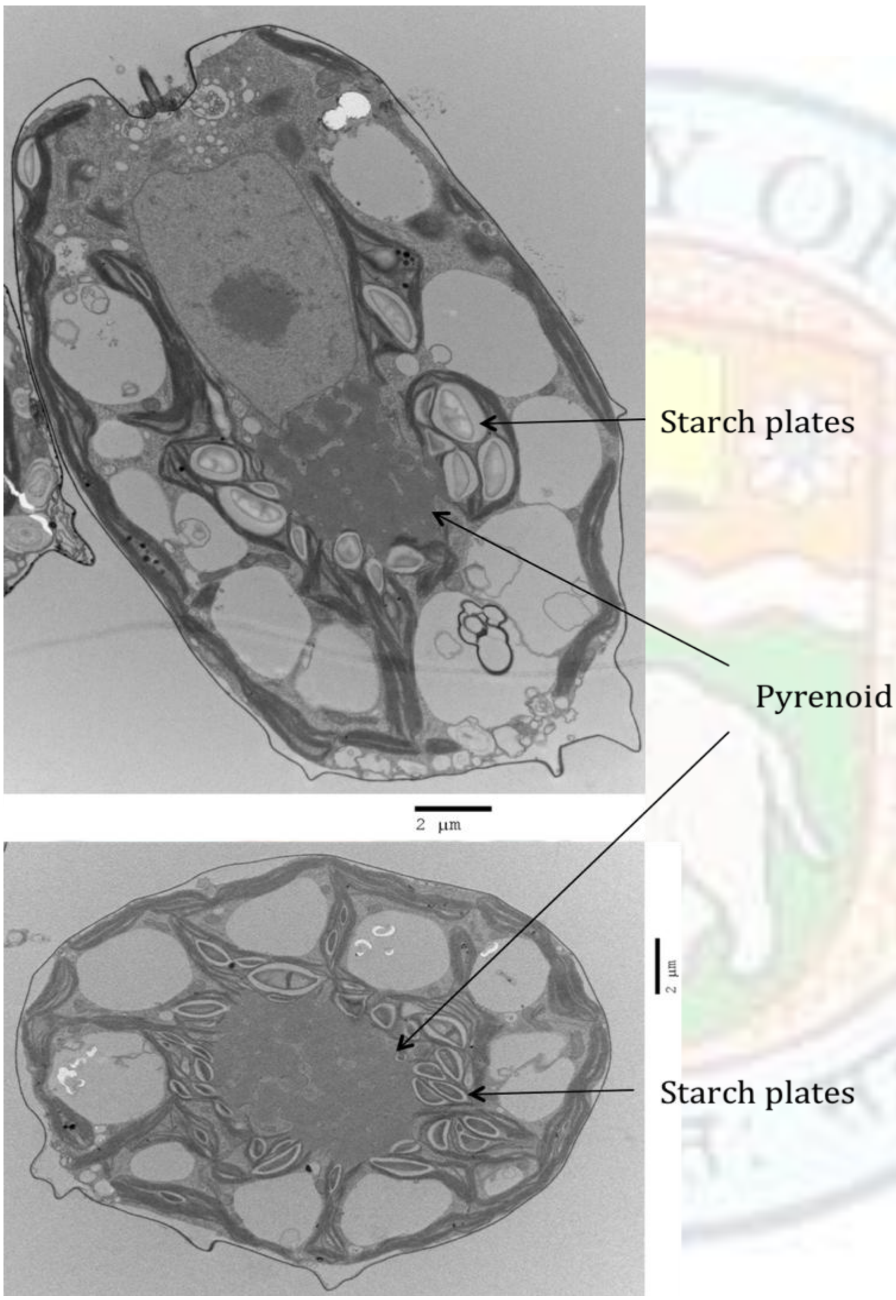


Figure: The pyrenoid in longitudinal and cross section of a green alga appears as a large, finely granular mass of polygonal profile surrounded by discontinuous shell of starch plates and penetrated by a system of tubules. Contractile vacuoles are also visible

Source: Author

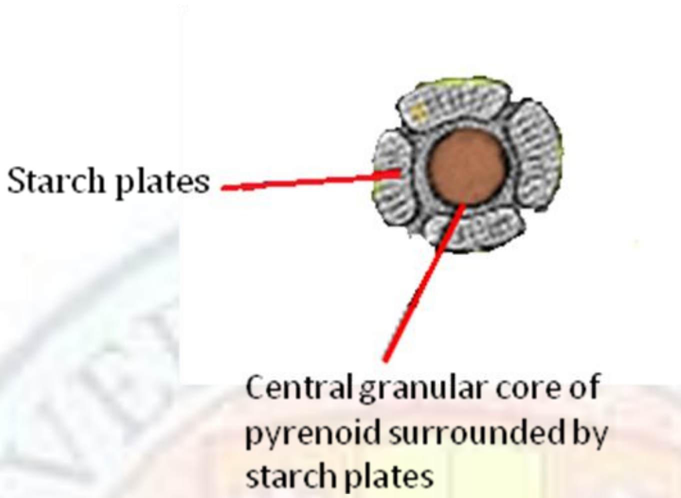


Figure: Pyrenoid structure

Source: Author

What is Eyespot or stigma?

The motile vegetative or reproductive cells of algae have a small pigmented bright reddish or brownish red eye-spot or stigma. It is usually associated with the chloroplast. It is considered as a photoreceptive organ. It consists of a curved pigment plate carrying the pigment and a biconvex hyaline lens in front. The motile vegetative and reproductive cells of *Chlamydomonas* have a small pigmented bright reddish or brownish red eye-spot or stigma which senses light. Eyespot is considered as a **photoreceptive** organ or the "**eye**" of the green algal cell and is involved in phototaxis (light dependent movement responses). It can be easily seen in the light microscope because of the huge accumulation of **carotenoids**. Using Electron microscopic studies it has been revealed that in a vertical section the eye-spot consists of one to four rows of **globules**. Each row comprises closely packed globules containing carotenoid pigments.

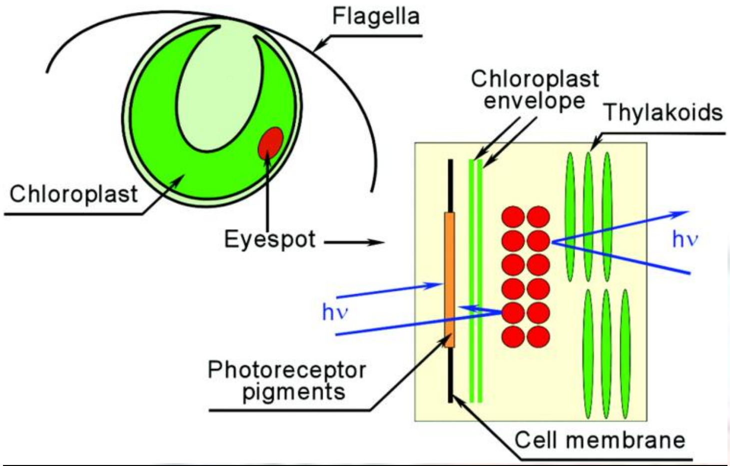


Figure: Schematic representation of the the eyespot in unicellular green algae *Chlamydomonas* .

http://www.pnas.org/content/99/13/8463/F1.expansion.html

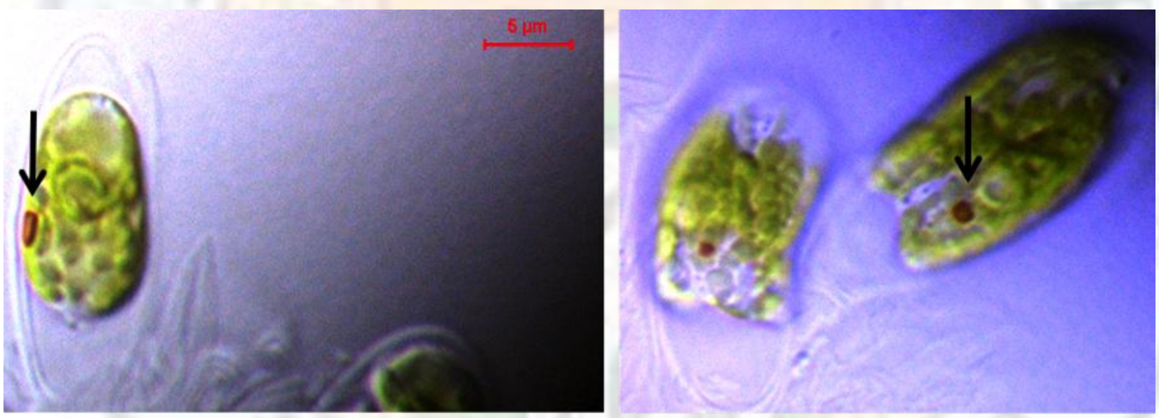


Figure: Light micrograph of a green alga showing the presence of eyespot- marked by arrowheads.

Source: Author: Arora M., 2011

Figure: Electron micrograph of a green algal cell showing ultrastructure of eyespot.

Source: Author

Pigments System

What are pigments?

Pigments are substances which absorb certain wavelengths of visible light. The different colours as seen when they are viewed in white light are due to the remainder of visible spectrum, either reflected or transmitted. The molecules of all organic pigments have a series of regularly alternating double and single bonds. The major groups of pigments in algae include **Chlorophylls**, **carotenoids** and **phycobiliproteins**. Chlorophyll *a* and *b* have been described from chlorophyceae. **Carotenoids** are grouped into **carotenes** (Oxygen-free hydrocarbons) and **xanthophylls** (oxygen derivatives of carotenes). Both carotenes and xanthophylls are present in chlorophyceae.

Table: Classification of algae: pigment and Size based

Source: Author

Algal Division/Class	Microplankton 20-200+ µm	Nanoplankton 2-20 µm	Picoplankton 0.2-2 µm	Major accessory Pigment
Chlorophyta: Chlorophyceae (Green algae)	+	+	+	chlorophyll *b*
Charophyta (Charophytes)	+	+	-	chlorophyll *b*
Euglenophyta (Euglenoids)	+	-	-	chlorophyll *b*
Phaeophyta (Brown algae)	+	+	-	chlorophyll $c1_{+}c2$, fucoxanthin
Chrysophyta (Yellow-brown algae)	+	+	+	chlorophyll $c1_{+}c2$, fucoxanthin

Pyrrhophyta (Dinoflagellates)	+	+	-	chlorophyll *c*2, peridinin
Cryptophyta (Cryptomonads)	+	+	-	chlorophyll *c*2, phycobilins
Rhodophyta (Red algae)	-	+	-	phycoerythrin, phycocyanin
Cyanophyta	+	+	+	phycocyanin, phycoerythrin

What are various types of chlorophylls and carotenoids present in chlorophyceae?

Chloroplast pigments in green algae are **similar** to those of the **higher plants**; chlorophyll a and b are present. In all algae, **chlorophyll *a*** is the major pigment and there is no member known to lack this pigment. **Chlorophyll *b***, **lutein** and **β-carotene** are important general accessory pigments of Chlorophyceae (Larkum and Howe 1997). Lutein is the main carotenoid. Some genera are found to have **siphonoxanthin** and its esters siphonein (Yoshi et al. 2003). Carotenoid pigments also commonly occur outside the chloroplasts, especially in resting cells and in the terrestrial *Trentepohlia*, as well as in the eye-spots of the motile stages. These yellow or red coloured substances, known as **haematochrome** are represented by two or more carotenoid pigments. In many cases they occur dissolved in fat globules.

Accumulation of carotenoids occurs under conditions of nitrogen deficiency, high irradiance or salinity. This is particularly true in *Dunaliella* where **β carotene** accumulates between thylakoids in the chloroplast, and *Haematococcus*, where **astaxanthin** accumulates in lipid globules outside the chloroplast (Hagen et al. 2000; Wang et al., 2003). Haematochrome is a general term for these carotenoids. Accumulation of haematochromes colour the cells orange or red, with haematochrome accumulating upto 8-12% of the cellular contents in *Dunaliella* (Orset and young, 1999). Animals cannot synthesize carotenoids and they acquire the pigments through the food chain from primary producers. Haematochromes are responsible for the coloring in fish, crustaceans and birds (such as the pink flamingos).

The plastids of green algae and land plants **lack** the **phycobilin** accessory pigments and thylakoid bound phycobilisomes (a characteristic pigment of **cyanobacteria**, red lagae and glaucophytes). No genetic traces of phycobilisomes have been found in green algal or land plant genomes.

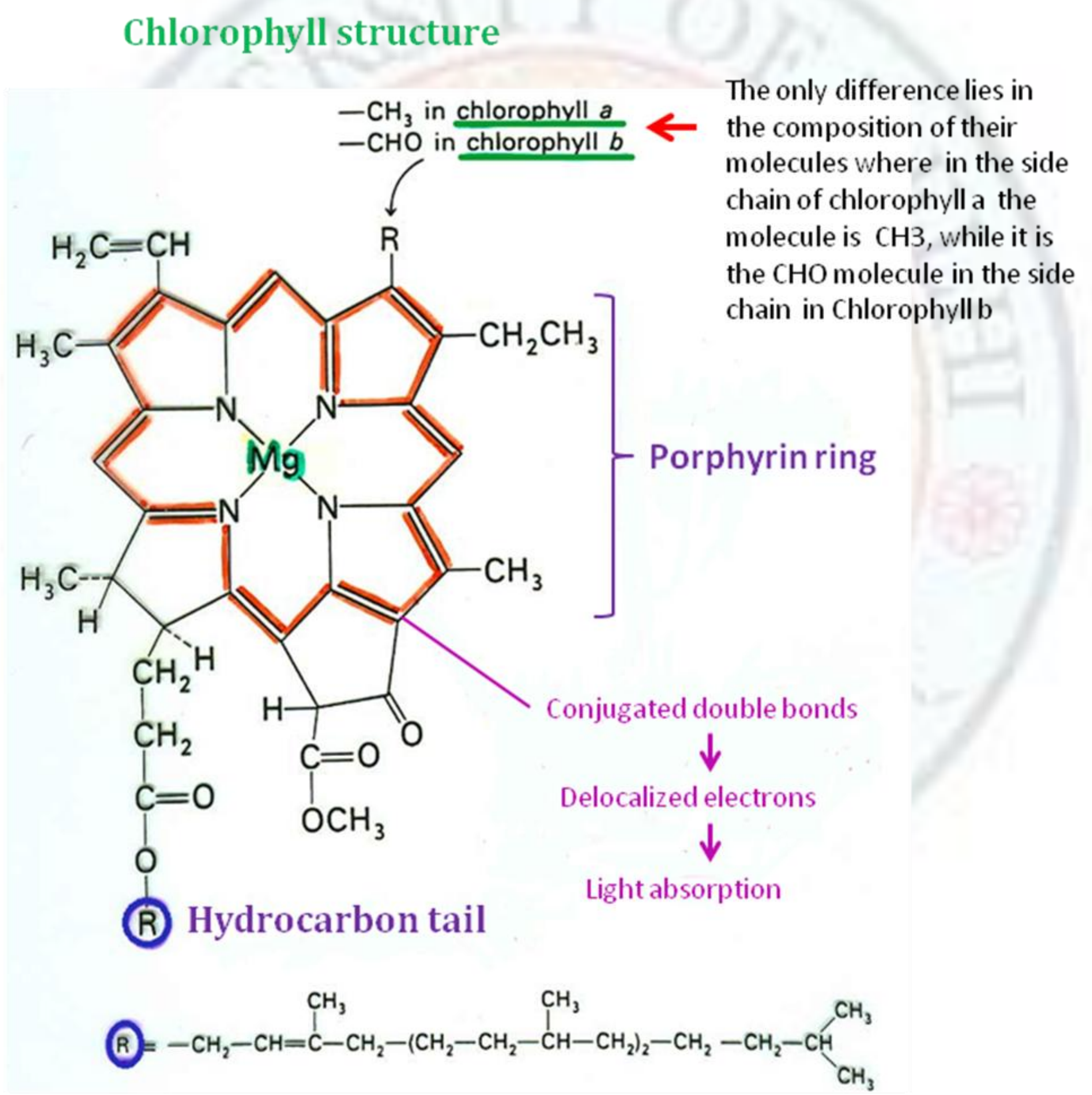
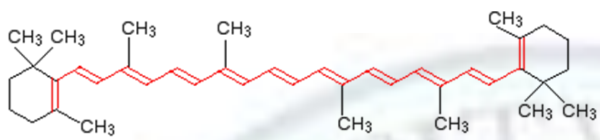
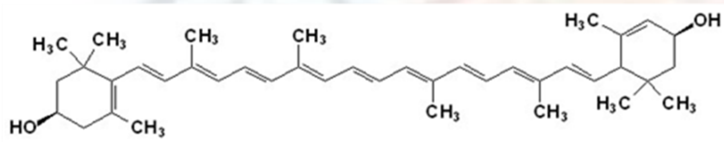


Figure: Structure of Chlorophyll molecules (Chl *a*, Chl *b*) showing a photon-absorbing porphyrin ring and a long hydrocarbon tail.

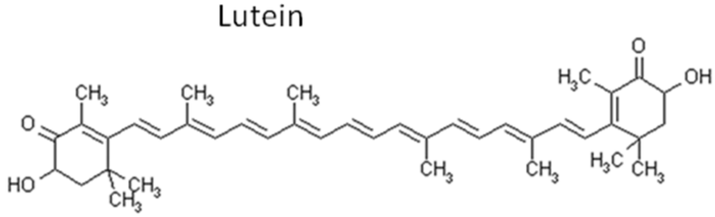
Source: http://facstaff.cbu.edu/~seisen/Photosynthesis.htm



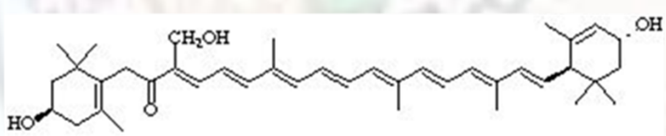
β carotene



Lutein



Astaxanthin



Siphonoxanthein

Figure: Carotenoids present in Chlorophyceae: Carotenoids are grouped into carotenes (Oxygen-free hydrocarbons) and xanthophylls (oxygen derivatives of carotenes). Hence β carotene and lutein are carotenes and astaxanthin and siphonoxanthin are xanthins.

Source:http://eng.ege.edu.tr/~otles/antioxidants/pages/antioxidants_that_are_naturally_found_in_foods.htm

Prochloron- Evolutionary significance

Discovery of *Prochloron*

Prochloron is a **cyanobacteria**- oxyphotobacteria (oxygenic photosynthetic **prokaryote**) and was discovered in 1975 by Lewin. They are well-known in tropical waters as symbionts with ascidians, the sea squirts.

Pigment composition of *Prochloron* and its significance in the evolution of green algae

All green algae contain chloroplasts with photosynthetic pigments - chl *a*, chl *b* and carotenoids. **Cyanobacteria**, on the other hand, only have chl *a* and phycobilins (phycobilins are absent in green algae and land plants). ***Prochloron*** is closely related to cyanobacteria but differ from other cyanobacteria because it contains **both chl *a/b*** and **lacks phycobiliproteins**. There are three known prochlorophytes (*Prochloron*, *Prochlorothrix*, and *Prochlorococcus*), cyanobacteria that have both chl *a* and chl *b*. No other prokaryotic life forms contain both chl *a*/*b*, but all photosynthetic eukaryotes (land plants and green algae) contain chl *a*/*b*. At present, there are studies being carried out on the photosynthetic machinery of *Prochloron*, because its morphology is distinctive among prokaryotes.

Evolution of green algal chloroplasts from *Prochloron* in terms of endosymbiotic theory

Evolutionary pathways for the origin of plastids (chloroplasts) in support with the **endosymbiotic hypothesis** is one of the most interesting and complex problems in the field of evolution and development. It was a great finding to discover a bacterium like ***Prochloron*** which contains all the light harvesting pigments which are present in chloroplasts. All **green algae** have **chl *b*** so the common ancestor of all green algae must be having chl *b*. According to the endosymbiotic theory this common ancestor should have been the **host** of the previously free-living symbiotic **bacterium** (prokaryotic alga) which ultimately developed into a chloroplast. Hence the green algae must have acquired their plastids from the **endosymbiosis** of a **photosynthetic bacteria** having **chl *b*** (such as *Prochloron*). It is believed that the outer membrane of the chloroplast envelope represents the vacuolar membrane of the host cell and the inner membrane represents the cell membrane of the photosynthetic bacteria.

The unique photosynthetic machinery of *Prochloron* among cyanobacteria make them fascinating to scientists who investigate the evolution of the characters in photosynthetic organisms. Learning more about the genetics of *Prochloron* will help researchers to determine relationships between these bacteria and other photosynthesizers, especially because of their distinct functional and structural photosynthetic features.

Prochloron cells are structurally comparable to the photosynthetic machinery of green plastids, having the thylakoids placed in the cytoplasm of the bacterial cells (Fig.). This feature forms the bases for the assumption that *Prochloron* is similar to the **symbiotic bacteria** which evolved into the first chloroplast within the autotrophic eukaryotes. The light harvesting pigment composition of *Prochloron* has similarity with both cyanobacteria and chlorophytes. In terms of endosymbiotic theory, it was proposed that *Prochloron* or its ancestor is the most probable precursor of the chloroplast found in photosynthesizing eukaryotes.

Land plants like green algae also have chloroplast surrounded by a double membrane and their chl *b* containing chloroplasts, too can be assumed to have arisen originally by the symbiosis of ***Prochloron*-like** prokaryotic cells.

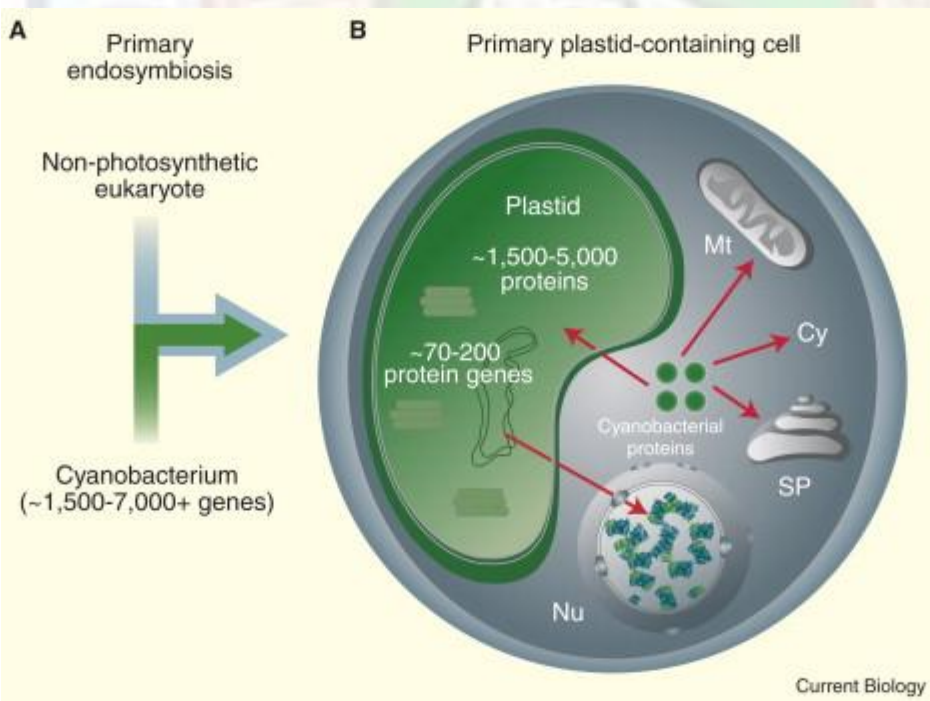


Figure: Endosymbiotic origin of Chloroplast (A) Primary endosymbiosis involving a **non-photosynthetic eukaryote** and a ***Prochloron*- like cyanobacterium** containing Chl *a* & **Chl *b***, (B) Schematic diagram of a chloroplast containing cell, chloroplast is structurally comparable to the *Prochloron* like cyanobacterium. The outer membrane of the chloroplast envelope represents the vacuolar membrane of the host cell and the inner membrane represents the cell membrane of the cyanobacterium. Where: Nu, nucleus; Cy, cytoplasm; SP, secretory pathway; Mt, mitochondrion.

Source: http://www.sciencedirect.com/science/article/pii/S096098220602447X

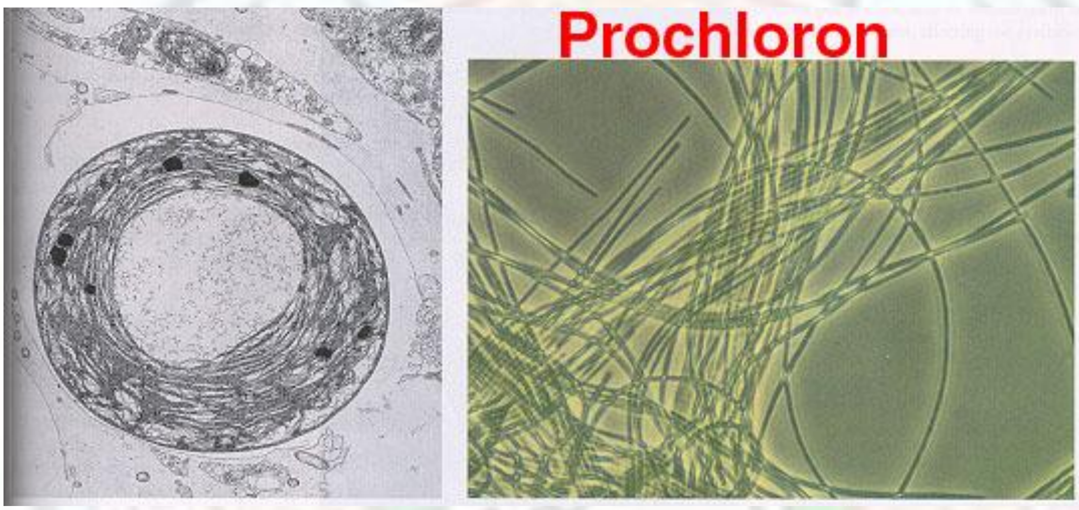


Figure: *Prochloron* cells are structurally comparable to the photosynthetic machinery of green plastids, having the thylakoids placed at the periphery in the cytoplasm of the bacterial cells

Source: http://www.emc.maricopa.edu/faculty/farabee/biobk/biobookcell2.html, http://delhi.tistory.com/253

Fine structure of *Prochloron*:

Prochloron is a unicellular prokaryotic alga containing both chl *a* and chl *b.* The cell wall of *Prochloron* resembles that of cyanobacteria. The thylakoids and cytoplasm are in the form of a wide peripheral band. The thylakoids are not present as single lamellae, as in cyanobacteria, but in pairs or, occasionally, in thicker stacks. Thylakoids and cytoplasm are not present in a large electron-transparent central zone. This zone may contain fibrils and electron-dense granules.

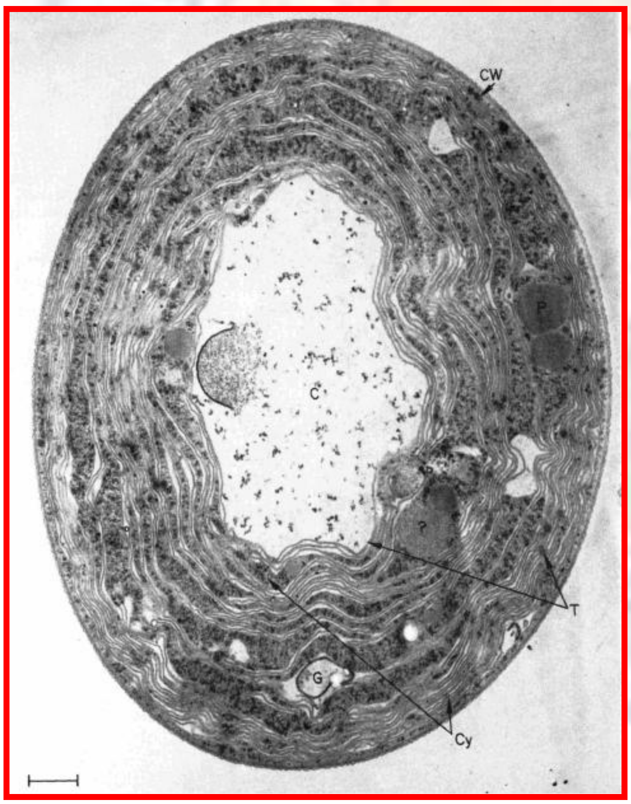


Figure: Electron micrograph of a *Prochloron* cell showing ultrastructure; where CW-cell wall, Cy-cytoplasm, T-thylakoids, G-Polyphosphate like granule

Source: http://onlinelibrary.wiley.com/doi/10.1111/j.1469-8137.1977.tb02210.x/pdf

How do the members of Chlorophyceae divide: aspects of mitosis and cytokinesis

Mitosis: In Chlorophyceae the nuclear envelope persists throughout mitosis, this is known as **closed mitosis**. The mitotic nuclei in these algae become dumbbell-shaped immediately before the completion of mitosis. Mitosis occurs and the two nuclei after separation drift towards each other (Pickett-Heaps, 1975).

Whereas in Charophyceae and land plants there is open mitosis. Here the mitotic spindles persist late during mitosis, therefore holding the daughter nuclei apart from each other.

Cytokinesis: Cytokinesis occurs by **simple furrowing.** Members of Chlorophyceae have a well developed cell wall and produce a set of microtubules that lie parallel to the plane of cytokinesis. This parallel set of microtubules is known as **phycoplast**.

Whereas in Charophyta, there is a persistent spindle that holds the daughter nuclei and keeps them separate until cytokinesis occurs. A few members of Charophyta and land plants produce a phragmoplast and cell plate. **Phragmoplast** are a double set of microtubules that lie perpendicul to the plane of cytokinesis.

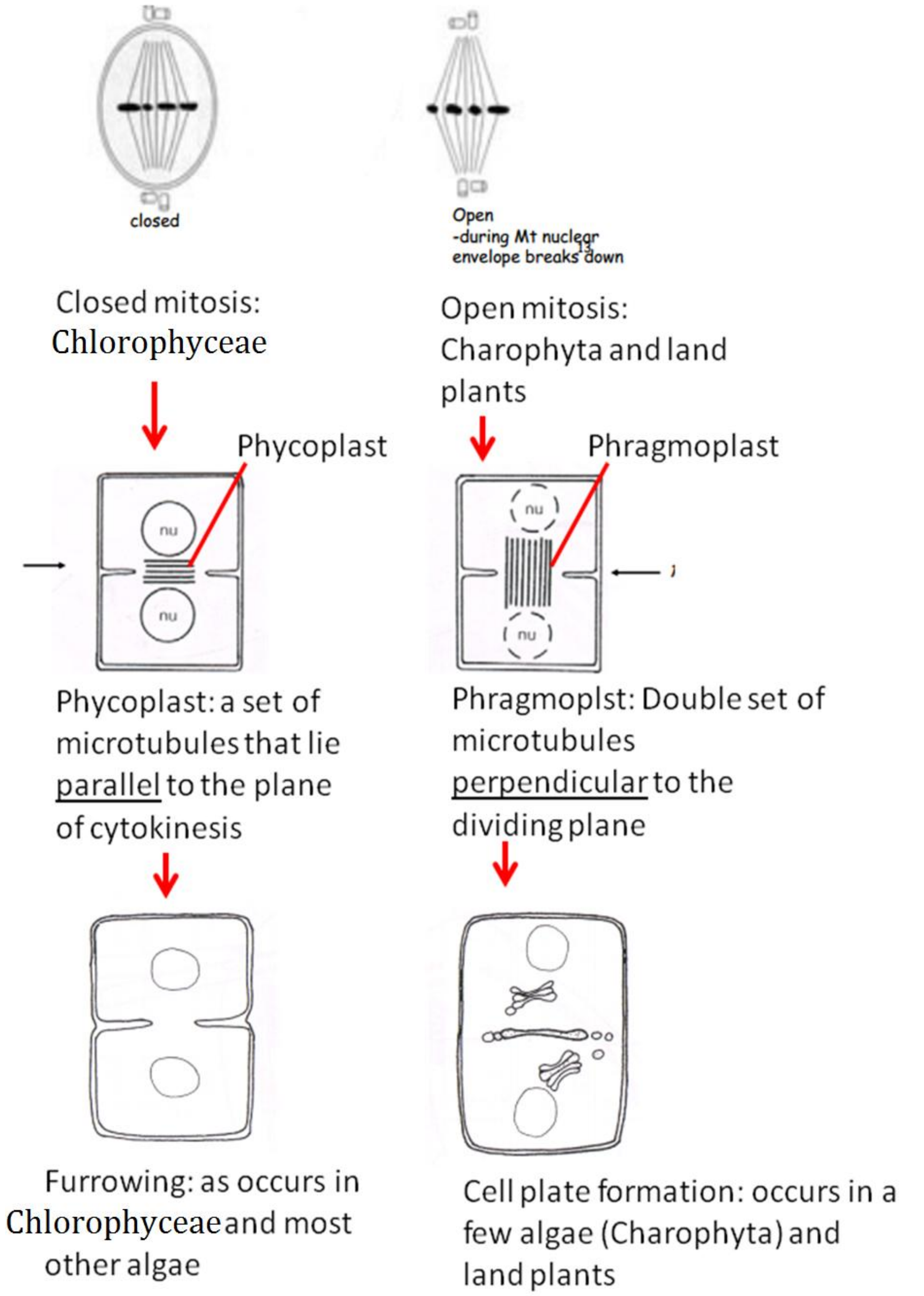


Figure: Diagrammatic representation of the method of cell division in Chlorophyceae, as compared to land plants and charophytes.

Source: http://bio.classes.ucsc.edu/bio120/Lecture%20notes/Chlorophytal_2.pdf

Biochemical features: Enzymes and microbodies

Differences in photorespiratory enzymes and organelles between Chlorophyceae, Charophytes and land plants:

Land plants and Charophytes use **glycolate oxidase** (GOXs) to break down the glycolate formed in the process of photrespiration. Glycolate oxidase together with the enzyme catalase, is localized within characteristic organelles known as peroxisomes. Peroxisomes of Charophytes are relatively large membrane bound organelles and are very similar to plant peroxisomes.

In contrast, Chlorophyceae use the enzyme **glycolate dehydrogenase** to break down the glycolate formed in the process of photorespiration. Small enzymatically distinct microbodies are present in these algae.

Similar to the plants, Charophytes are characterized by the presence of **Cu/Zn superoxide** dismutase enzyme system, whereas this enzyme is **absent** in Chlorophyceae and other green algae.

Summary

The cells constituting the thallus are eukaryotic and thus contain all the cell organelles such as the definitely organized nucleus, plastids, mitochondria, Golgi bodies and endoplasmic reticulum. Starch is the reserve food. The cell wall has cellulose as the main structural polysaccharide. The protoplast is bounded by a thin and semi permeable plasma membrane. In a few primitive forms, the protoplast lacks the cell wall and is naked. The cytoplasm possesses many small vacuoles or there is a large central vacuole. The pigments are localized in the green plastids known as chloroplasts. The chloroplasts normally contain the pyrenoids surrounded by a sheath of starch. The shape of chloroplast shows much variation. Usually there is a single nucleus in each cell, but the members of Siphonales and Cladophorales are coenocytic. Most of the flagellate cells have a photosensitive red eye spot or stigma in the anterior portion, near the flagellar base. The main pigments are chlorophyll a and b, but α and β carotenes and xanthophylls are also present. Members of Chlorophyceae lack the phycobilin accessory pigments and thylakoid bound phycobilisomes (a characteristic pigment of cyanobacteria, red lagae and glaucophytes). Cyanobacteria only have chl *a* and phycobilins. *Prochloron* is closely related to cyanobacteria but differ from other cyanobacteria because it contains both chl *a*/*b* and lacks phycobiliproteins. This suggests that *Prochloron* is similar to the symbiotic bacteria which evolved into the first chloroplast within the autotrophic eukaryotes. Cell division in Chlorophyceae occurs by closed mitosis and phycoplast formation.

Exercise/ Practice

1. Give an account of cell structure in Chlorophyceae. Draw a labeled diagram of a chlorophycean cell showing ultrastructural details.

2. Draw an ultrastructure diagram of T.S. of a typical chlorophycean flagellum.

3. Distinguish between chloroplast, pyrenoid and eyespot.

4. Describe the function of pyrenoid and eyespot.

5. What is the main function of contractile vacuole?

6. What pigments are present in Chlorophyceae?

7. *Prochloron* is a cyanobacteria but it lacks phycobillins and have the pigment composition same as Chlorophyceae. Elucidate its evolutionary significance.

8. Describe the fine structure of *Prochloron* with the help of labeled diagram.

9. Describe the process of mitosis and cytokinesis in Chlorophyceae. What is a phycoplast?

10. Describe the various shapes that chloroplasts take in Chlorophyceae along with examples.

11. Write true/false against the following statements.

(i) *Prochloron* is a prokaryote with chlorophyll *a* and *b*.

(ii) Flagella in the Class Chlorophyceae are isokont and of whiplash type.

(iii) Starch is the reserve food material in Chlorophyceae.

(iv) The endosymbiont hypothesis proposes that the chloroplasts originated when a non-photosynthetic eukaryote engulfed a *Prochloron*- like cyanobacterium.

(v) The bright red colour of the eyespot is due to the accumulation of carotenoids.

12. Fill in the blanks:

(i) *Prochloron* belongs to the Division…………………….

(ii) The principal photosynthesizing pigments in Chlorophyceae are…………………

(iii) ……………………………is a photoreceptive structure and is involved in phototaxis (light dependent movement response) of a green algal cell.

(iv)Cytokinesis in Chlorophyceae is associated with the formation of a set of microtubules that lie parallel to the plane of cytokinesis and is known as……………….

(v) Mitosis in Chlorophyceae is of……………………type in which the nuclear envelope persists throughout mitosis.

Glossary

Axoneme: Central two and nine peripheral doublet microtubules of a flagellum.

Basal body: bottom part of a flagellum beneath the transition zone; basal bodies divide to perpetuate the flagella.

Carotenoid: yellow, orange, or red hydrocarbon fat-soluble pigment

Cellulose: polysaccharide composed of -1, 4 linked glucose molecules that forms the main skeletal framework of most algal cell walls.

Chlorophyll: fat soluble, green pigment

Chloroplast: plastid with chlorophyll

Contractile vacuole: vacuole fed by smaller vesicles that expel water and solutes rhythmically to the outside of the cell.

Dictyosome: stack of vesicles in a Golgi apparatus

Disc or Thylakoid: membrane sac in the chloroplast

Electron-dense: a material that appears dark in electron micrographs

Electron-transparent: a material that appears light in the electron micrographs

Eukaryotic: a cell having membrane-enclosed organelles such as the nucleus and mitochondria.

Eyespot: red to orange area in a cell, composed of lipid droplets

Phototaxis: movement of a whole organism toward (positive) or away from (negative) light.

Pyrenoid:proteinaceous area of the chloroplast associated with the formation of storage product.

Stigma or eyespot: group of pigmented lipid bodies that are associated with phototaxis.

Ultrastructure: is the detailed structure of a biological specimen as seen only under electron microscope.

Xanthophyll: a carotenoid composed of an oxygenated hydrocarbon.

References/ Bibliography/ Further Reading

1. Alexopoulos C.J. & Bold H.C. 2003. Algae and Fungi. Texas.

2. Barsanti, L., Gualtieri, P. 2006. Algae: anatomy, biochemistry and biotechnology, CRC Press, New York, 97-126.

3. Arora M. 2011. Complexity and population regulation in unicellular algal cultures of *Tetraselmis indica* PhD thesis, Newcastle University.

4. Arora M. *et al.* 2013. *Tetraselmis indica*, a new species isolated from salt pans (Chlorodendrophyceae, Chlorophyta). *European Journal of Phycology,* 48: 61-78.

5. Desikachary T.V. 1957. Electronmicroscopy and algology. *Proceedings of the Indian academy of Sciences*. 46:54

6. Fritsch F.E. 1935. The structure and reproduction of algae. Vol.I, Cambridge University Press.

7. Fritsch F.E. 1944. Present day classification of algae. *Botanical Review.* 10:233.

8. Graham, L.E. & Wilcox, L.W. 2000. Algae, Prentice-Hall, Inc.

9. Hagen C. et al. 2000. Accumulation of secondary carotenoid in flagellates of *Haematococcus pluvialis* (Chlorophyta) is accompanied by an increase in per unit chlorophyll productivity of photosynthesis. *European Journal of Phycology*. 35:75-82

10. Larkum, A.W.D. and Howe, C.J 1997. Molecular aspects of light harvesting processes in algae. *Advances in Botanical Research.* 27:258-330.

11. Lee, R.E. 2008. Phycology, Fourth ed. Cambridge univ. press.

12. Leliaert F. *et al.* 2012. Phylogeny and molecular evolution of the green algae. *Critical Reviews in Plant Sciences.* 31: 1-46

13. Leliaert F. *et al.* 2011. Into the deep: new discoveries at the base of the green plant phylogeny. *BioEssays.* 33: 683–692

14. Orset S. & Young A.J. 1999. Low temperature-induced synthesis of α-carotene in the microalga *Dunaliella salina*. *Journal of Phycology*. 35:520–527.

15. Pickett-Heaps J.D. 1975. Green Algae: structure, reproduction and evolution in selected genera. Sinauer Associates, Inc. Publishers, Massachusets.

16. Round F.E. 1965. The biology of the Algae. Edward Arnold Ltd. London.

17. Smith G.M. (Ed). 1951. Manual of Phycology. *Chronica Botanica.* Waltham mass.

18. Sambamurty A.V.S.S. 2005. A text book of algae. I.K. International, New Delhi.

19. Wang, B. *et al.* 2003. Astaxanthin accumulation in *Haematococcus pluvialis* (Chlorophyceae) as an active photoprotective process under high irradiance. *Journal of Phycology.* 39:1116–24.

20. Yoshi *et al.* 2003. photosynthetic pigment composition in the primitive green alga *Mesostigma viride* (Prasinophyceae): phylogenetic and evolutionary implications. *Journal of Phycology*. 39: 570-576