Fig. 1 Phylogeny of eukaryotes, based primarily on Brown et al. (2013), Cavalier-Smith et al. (2014), Kamikawa et al. (2014), Yabuki et al. (2014), Burki et al. (2016), and Leger et al. (2017). Groups with bulbous branches are examined in more detail in Figs. 2–5. Groups with narrow branches do not belong to well-established supergroups and are not illustrated separately; those covered in the Handbook are shown in blue and are as follows: ➤ Cryptophyta; ➤ Haptophyta; ➤ Centrohelida; ➤ Ancyromonadida; ➤ Malawimonadidae; ➤ Gymnosphaerida; ➤ Heliomonadida.
[very simplified] scheme of plastid endosymbioses

(more in the course of Protistology )
oceanic phytoplankton – „basic scheme“ of the RECENT global structure

Figure 3 - Variations saisonnières des peuplements de phytoplancton (en bleu : haptophytes; en vert : Prochlorococcus; en jaune : Synechococcus; en rouge : diatomées). Les diatomées abondent au printemps aux hautes latitudes, où les haptophytes dominent le reste de l’année. Prochlorococcus et Synechococcus dominent en permanence dans les régions tropicales.
Climatological map showing the distribution of annual marine NPP (a) NASA Ocean Biogeochemical Model and (b) Vertically-integrated Production Model (VGPM) for the period from September 1998 to 2011 (Rousseaux – August 1999 (Blue < 100 g C m⁻³, Green > 110 g C m⁻³ and < 400 g C m⁻³, Red > 400 g C m⁻³) (Rutgers Institute of Marine and Gregg, 2014). Globally, diatoms accounted for about 50 per cent of NPP while coccolithophores, chlorophytes and cyanobacteria accounted for about 20 per cent, 20 per cent and 10 per cent, respectively. Diatom NPP was highest at high latitudes and in equatorial and eastern boundary upwelling systems. Coastal Sciences, http://marine.rutgers.edu/opp/. Coastal ecosystems (red – green) and the permanently stratified subtropical waters of the central gyres (blue) each account for ~30 per cent of the ocean’s NPP, whereas the former accounts for ~8 per cent of the ocean’s surface area compared to ~60 per cent for the open ocean waters of the subtropics (Gleider et al., 2001; Marnahón et al., 2003; Muller-Karger et al., 2005).
palaeozoic vs. recent marine phytoplankton

Götz & Feist-Burkhardt, 2012, Palaeogeogr, Palaeoclim, Palaeoecol
Le Hérissé et al., 2009, Palynol.
Fig. 2. Molecular timescale for Heterokonta using minimum and maximum inference of the age of the root at 900 Ma (grey) and 1200 Ma (black), respectively (Douzery et al. 2004), and with Rhizosolenia root constrained to 93 Ma based on biochemical isoprenoid evidence in this genus by Sinninghe-Damsté et al. (2004). A grey box indicating the time point of the P/T boundary at 250 Ma as estimated from the minimum and maximum age priors (program constraints as above) is placed over tree. a = origin of the pigmented Heterokonta, b = origin of the diatoms. All time estimates in the table inset are shown with the time as estimated with a 900 or 1200 Ma constraint on the crown group radiation and their standard error. Original data set found in Medlin et al. (1997). Heterotrophic taxa are coloured in grey.
Fig. 3. Molecular timescale for haptophytes using minimum and maximum inference of the age of the root at 900 Ma (grey) and 1200 Ma (black), respectively (Douzy et al. 2004). A grey box indicating the time point of the P/T boundary at 250 Ma as estimated from the minimum and maximum age priors (program constraints as above) is placed over tree. a = divergence of the two classes, b = radiation of the order Prymnesiales. All time estimates in the table inset are shown with the time as estimated with a 900 or 1200 Ma constraint on the crown group radiation and their standard error. Original data set found in Edvardsen and Medlin (2007). Heterotrophic taxa are coloured in grey.
Fig. 4. Molecular timescale for dinoflagellates using minimum and maximum inference of the age of the root at 900 Ma (grey) and 1200 Ma (black), respectively (Douzery et al. 2004). A grey box indicating the time point of the P/T boundary at 250 Ma as estimated from the minimum and maximum age priors (program constraints as above) is placed over tree. \( a = \) divergence of the parasitic and free-living dinoflagellates. All time estimates in the table inset are shown with the time as estimated with a 900 or 1200 Ma constraint on the crown group radiation and their standard error. Original data set found in John et al. (2003) with Amoebophrya spp. added to obtain Point \( a \). Heterotrophic taxa are coloured in grey.
dramatic decline of diversity (oceans > continents)
extinction of multiple high-order lineages – including apparent algal/protist groups
dramatic fluctuation in sea level
fluctuations in global temperature
jumps in primary productivity (ratio of C12/C13)
changes in basic features of rivers (braided vs. meandering)
long-term change in vegetation patterns
acidification of oceans and strong increase in their oxygen limitation / anoxia
increase in atmospheric CO2, decline in oxygen concentration
recent estimates of time scale: between $251.941 \pm 0.037$ and $251.880 \pm 0.031$ My

Burges, 2014, Nature 111

Siberian traps
athmospheric concentration of oxygen
Haptophyta

lineage including organisms with key effects on global ecosystem (carbon cycle, dimethylsulfide);
c.a 300 recent species, only about 15 species in freshwater [incl. Corcontochrysis noctivaga]
some marine and brackish taxa produce toxins (e.g. Prymnesium – fish poisoning)
Haptophyta – phylogeny and systematics

Pavlovophyceae
Coccolithophyceae

Edvardsen & Medlin, 2007
**Coccolithales**

coccoliths – calcium carbonate scales on cellular surface

holococcoliths – develop externally on cells

heterococcoliths – develop inside the cells, complex 3D shapes

calcification: \( 2 \text{HCO}_3^- + \text{Ca}^{2+} = \text{CaCO}_3 + \text{CO}_2 + \text{H}_2\text{O} \)

haptophytes make up about 50% of total inorganic carbon pump in the oceans
Figure 2 - Typical coccolithophore life-cycle, and three examples
Figure 3 - Variations saisonnières des peuplements de phytoplancton (en bleu : haptophytes; en vert : Prochlorococcus; en jaune : Synechococcus; en rouge : diatomées). Les diatomées abondent au printemps aux hautes latitudes, où les haptophytes dominent le reste de l’année. Prochlorococcus et Synechococcus dominent en permanence dans les régions tropicales.
white tides and - dimethylsulfide - source for the condensation nuclei of clouds
Emiliania huxleyi – one of the most frequent recently occurring eukaryots on Earth

E. hux. is evolutionarily very young – only since Pleistocene
Emiliania huxleyi (Isochrysidales, Noelaerhabdaceae)
Gephyrocapsa oceanica  
(Isochrysidales, Noelaerhabdaceae)  
- 7.3 my to recent

Coccolithus pelagicus  
(Coccolithales, Coccolithaeae)  
- 66 my to recent

Discosphaera tubifera  
(Syracosphaerales, Rhabdosphaeraceae)  
- 16 my to recent

Young et al., 2003, Journal of Nannoplankton Research
http://www.mikrotax.org/Nannotax3/
Braarudosphaera bigelowii
(Braarudosphaeraceae)
- 100.5 my to recent

- an old lineage (since Mesozoic)
- coccoliths develop extracellularly (i.e. probably not homological with other groups)
- probably belongs to Prymnesiales, together with "naked" haptophytes
- haploid stage is known as Chryschromulina parkeae
- in cells - endosymbiotic coccoid, nitrogen-fixing cyanobacterium
- typical coastal planktonic organisms

http://www.mikrotax.org/Nannotax3/
Hagino et al., 2013, Plos One
Coccolithophores and global calcification

Betzler et al., 2017, IODP; Anderson, 2016, Oceanbites
calcifying organisms, such as Coccolithophores, provide long-term carbon sink mechanisms, compensating for instantaneous CO$_2$ excursions

Archer et al., 2009, AREPS
NOAA Climate.gov
calcification:

\[ 2 \text{HCO}_3^- + \text{Ca}^{2+} = \text{CaCO}_3 + \text{CO}_2 + \text{H}_2\text{O} \]

only about 0.5% of \(\text{CaCO}_3\) produced at the surface reaches the ocean floor

DIC is about 15% higher in ocean depths and this is of key importance for atmospheric \(\text{CO}_2\) levels

intense planktonic calcification leads to increased \(p^{\text{CO}_2}\) in surface waters and, consequently, lower uptake of atmospheric \(\text{CO}_2\)
*Phaeocystis* – flagellate with sticky chitinous filaments

genus *Phaeocystis* - ca 10% of global DMS production, coastal white tides
Chrysochromulina

unicellular, planktonic marine [rarely freshwater] flagellates
haptonema usually prominent – attachment to the substrate or to the prey
mixotrophy - phagotrophy, osmotrophy

zdroj: nordicmicroalgae.org
Cryptophyta

cryptophytes – flagellates with (red algal) nucleomorphs, phycobilins (without phycobilisomes) and trichocysts (heterotrophic nutrition)

plankton of freshwater and seas, about 200 species
Cryptomonas – most frequent freshwater genus

marine cryptophytes – e.g. *Rhodomonas* a *Chroomonas* mostly (sub-)tropical shelf seas
**Dinophyta** (= *Dinozoa, Dinoflagellata*)

mostly phototrophic group belonging to *Alveolata*

- Dinokaryon – nucleus lacking any histons, i.e. permanently condensed DNA

- Oldest fossils - 600 mil. let – late Precambrium
  (the morphotypes are more or less identical with some recent cold-water cysts of dinoflagellates)

- About 2000 species, mostly in marine plankton, about 10% in freshwater, often as parasites

- About half of species heterotrophic, lacking plastids; often phagotrophic
  secondary plastids from red or green lineage; tertiary plastids from multiple hosts

In general – many symbiotic events in evolution (including kleptoplastids)
Original (red algal) genomes of dinoflagellate plastids are reduced to single-gene circles (and, moreover, most genes were transferred to nucleus). Tertiary plastids in dinoflagellates in three lineages. Green secondary plastids in one lineage.

Fig. 3. An illustration showing the major events in plastid evolution in the alveolate lineage, with an emphasis on the dinoflagellates. The (+) indicates plastid gain, the (−) indicates plastid loss, and the (~) indicates the origin of the apicoplast in the apicomplexans. The putative multiple independent losses of the peridinin plastid in the dinoflagellate lineage are not shown. Perid. is Peridinium, Lepido. is Leptodinium, and chl. is chlorophyll.
Dinophysis - red tides, toxins in marine habitats
symbiotic, heterocytous cyanobacteria (nitrogen-fixing) otherwise heterotrophic (sub-)tropical marine plankton
Peridinium

Gymnodinium

freshwater planktonic dinoflagellates
Ceratium – ecologically the most important dinoflagellate genus; both marine and freshwater phytoplankton
*Noctiluca scintilans* (seasparkle, svítílka)
cells up to 2 mm, heterotrophic or
with symbiotic green algae

[YouTube video](https://www.youtube.com/watch?v=7kyP0XsF0zM)
toxic water blooms in shelf seas - saxitoxin

...and the waters that were in the river were turned to blood. And the fish that were in the river died; and the river stank and the Egyptians could not drink of the water of the river...
Exodus 7: 20-21

a dinoflagellate or cyanobacterium?
**Symbiodinium („zooxanthella“)**

probably a monophyletic lineage; obligate endosymbionts of eukaryotes mostly as intracellular symbionts

hosts: Cnidaria (incl. corals), platyhelminths, Porifera, bivalvs, foraminifers, ciliates

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Figure 2. A symbiotic relationship between corals and Symbiodinium

http://mucholderthen.tumblr.com

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coral bleaching

marinesciencetoday.org
basic structural features of stramenopile flagellated cells
seaweed  raphidophyte flagellate
Riisberg et al., 2009, Protist

Figure 2. Protein and rDNA phylogeny of heterokonts. Combined lsu, ssu, actin, β-tubulin, cox1 and hsp90 phylogeny of Ochrophyta, Bigya and Pseudofungi. PAML fast-evolving site category 8 for both rDNA and proteins has been removed (Yang 1997, 2007; Kumar et al. unpublished) (4632 characters). For further information, see legend for Figure 1.
**Chrysophyceae** (incl. *Synurophyceae*)

mostly freshwater flagellate and mucilaginous organisms; about 700 species

*Dinobryon* – flagellates in vase-shaped chitinous shells

*Paraphysomonas* – genus with rudimentary plastid and silicate scales

endogenous silicate stomatocysts

both marine and freshwater species
"Synurophyceae" mainly genera *Mallomonas* a *Synura*

freshwater flagellates with silica scales; about 250 species

http://www.flickr.com/photos/joelmancuso/110623789/

bioindication of environmental dynamics; palaeoecological studies, "blooms" especially in boreal ecosystems
biogenesis of silicate scales

Fig. 5.32. Scale formation in *M. caudata*. (Wujek & Kristiansen 1978).

Fig. 5.33. Bristle formation in *M. caudata*, transverse sections of successive stages. (Wujek & Kristiansen 1978).

silica deposition vesicles

development of posterior bristles in *Mallomonas splendens*
Synura
colonial relatives of mallomonads
Hydrurus (foetidus)

mucilaginous thallus adapted to living in fast flowing water
**Dictyochophyceae**

small but ecologically important group of phototrophic marine flagellates

silico-flagellates

*Dictyocha*

cold oceans, phytoplankton

since Mesozoic - 120 mya; bioindication of cold periods in the geological past
Diatoms – Bacillariophyceae

- Centric and pennate types
- Silicate shell (frustule) made of two parts
Frazer, 2010, Diatoms, or The Trouble With Life in Glass Houses
E. Haeckel: Kunstformen der Natur
life cycle, frustule structure
Figs 12–16. Summary of main types of sexual reproduction found in the major clades of diatoms. Figs 12–13, 15–16 reproduced from Kaczmarska et al. (2013), with permission from Diatom Research.

Fig. 12. Oogamy, female gametangium.
Fig. 13. Oogamy, male gametangium.
Fig. 14. Anisogamy in araphid diatoms with amoeboid spermatia released from gametangia with appendages to draw egg when it is released to the spermium. Reproduced from Sato et al. (2011), open access permission from Plos ONE.
Fig. 15. Isogamy in raphid diatoms within copulation envelops.
Fig. 16. Physiological anisogamy with one motile gamete moving across conjugation tube to fertilise a non-motile gamete.
Fig. 2. Phylogeny inferred with the Bayesian analysis. Major clades are collapsed into triangles for clarity. PP > 50% are placed at each node. Pink, clade 1; green, clade 2a; blue, clade 2b.
Medlin, 2016, Phycologia
zygote, auxospore, initial cell

vegetative diminution cycle (*morphological allometry*)

Navicula

Gomphonema

http://craticula.ncl.ac.uk/

rbg-web2.rbge.org.uk/algae/sellaphora
- oldest diatoms – since early Mesozoic
- only since Miocene (-25 mya) they are a dominant, especially in phytobenthos

- biomonitoring – water treatment technology;
- confusing estimates of global species diversity
Sellaphora pupula

- Pseudoblunt
- Tidy
- Large
- Cf. rectangular
- Pseudocapitate
- Elliptical
rbcL–based phylogeny of Sellaphora...; how many species?
Figure 3 - Variations saisonnières des peuplements de phytoplancton (en bleu : haptophytes; en vert : Prochlorococcus; en jaune : Synechococcus; en rouge : diatomées). Les diatomées abondent au printemps aux hautes latitudes, où les haptophytes dominent le reste de l’année. Prochlorococcus et Synechococcus dominent en permanence dans les régions tropicales.
Eunotia

Gomphonema

Gyrosigma

Achnanthes

Bacillaria