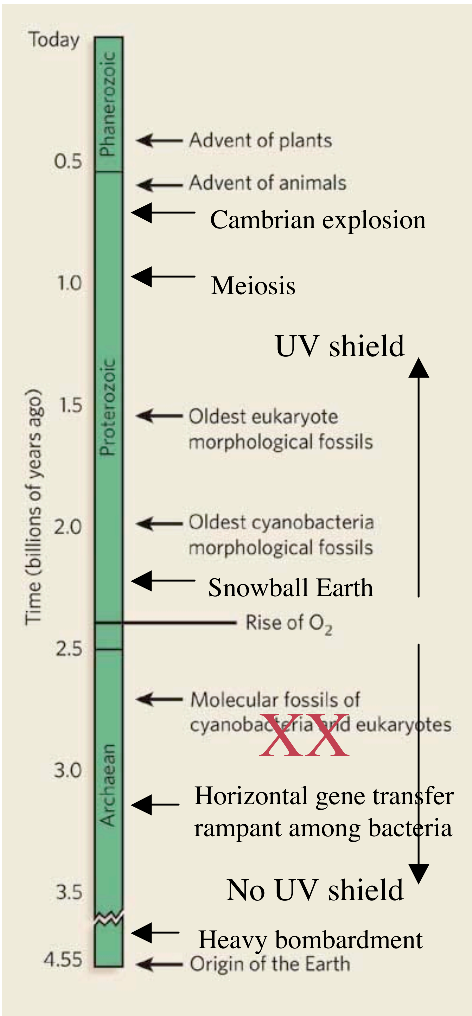
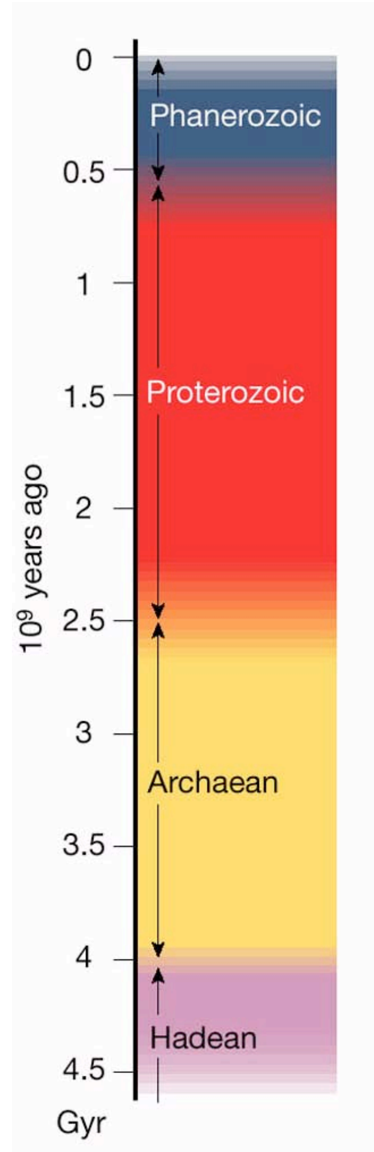
IV. Major events in biological development on Earth

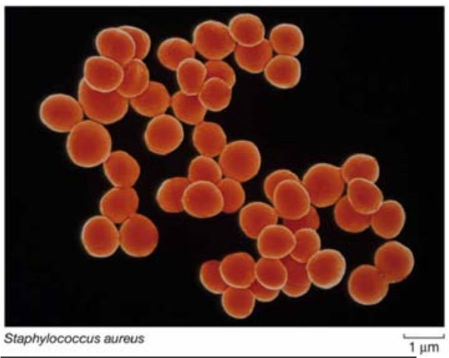


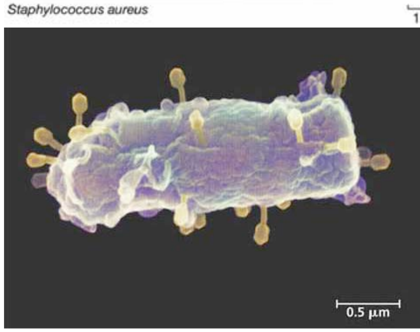
We are trying to fill in some of the biological details in the "timelines" shown here.

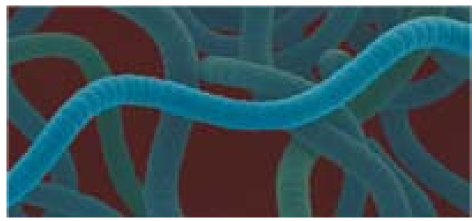


The Hadean/Archean biological world

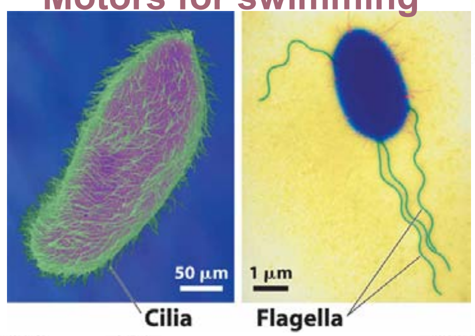
Prokaryotes: Most successful organisms on Earth. The only life for over 2 Gyr, most (?) still with us. Essentially infinite lifetime for colonies. Note the complexity!
→ No organelles (eukaryotic cells only), smaller genome, no sex, but other abilities like extreme adaptation (see “extremophiles”), and especially *horizontal gene transfer*.



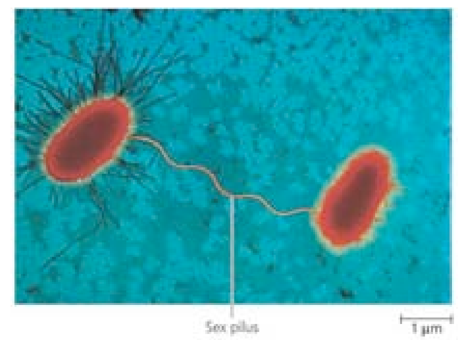




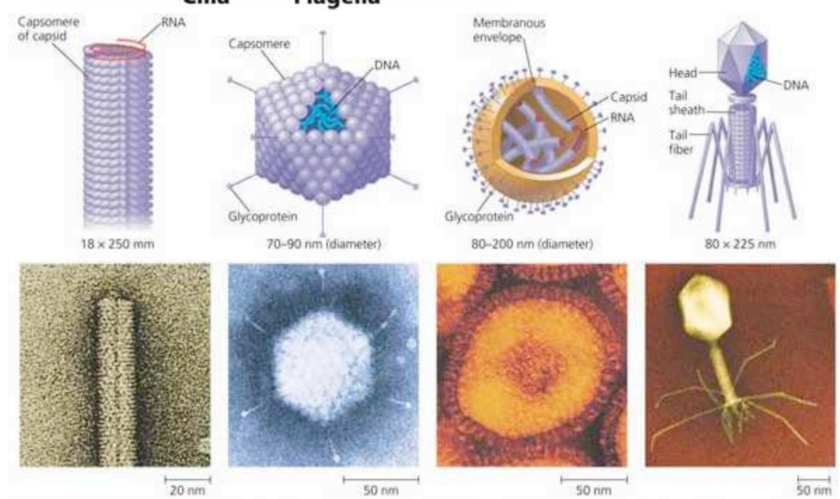
Motors for swimming



Horizontal (lateral) Transfer of genetic material



(and viruses)



Hadean/Archaean Biological World, continued:

Prokaryotes rule from beginning of cellular life to the Precambrian/Cambrian transition ~ 0.6 Gy ago

The next few ***evolutionary trees*** are meant to emphasize two points:

1. The prokaryotes consist of *two* domains, the ***bacteria*** and the ***archaea***. They are both separated from the more complex domain of the ***eukaryotes***, but most evidence suggests that the eukaryotes are more closely related to archea.

(See textbook for discussion of the simplest of these trees and how they are constructed.)

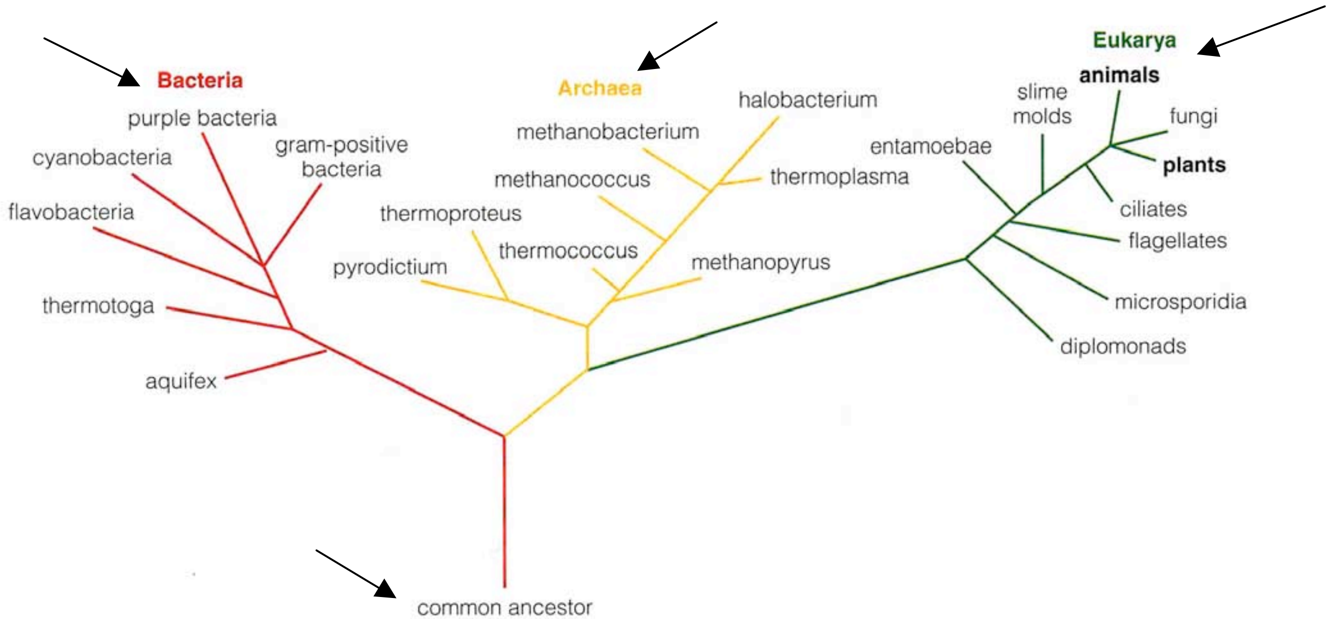
Notice the large number of extremophiles in archea, and the methanogens, which provided the greenhouse gas for early Earth and kept it from suffering a global glaciation (at least until the cyanobacteria took over)

2. Bacteria and archaea were able to create unimaginable biological diversity because of a talent that few "higher" organisms possess: the ability to exchange genetic material with each other, even with very distantly related species. This property remains a dominant reason why bacteria are so successful with their present hosts (e.g. us).

This process is called *horizontal* or *lateral* transfer of genetic material. You will see one evolutionary tree for prokaryotes that has most of the known (~ 2005) horizontal transfer connections marked.

Tree of life from comparisons of small subunit ribosomal RNA (shared by all living things) sequences

(same as illustration in text)



Main feature: **Three domains**. Bacteria, Archaea, and Eukarya.

Notice also "**common ancestor**" at the "root." This intriguing designation only says that the diversification had to begin somewhere on this tree; however it all depends on the most fundamental idea, that all organisms must be related by lineage. With today's understanding of the genetic code, and the fact that all known life shares the *same* code, uses the *same* amino acids, etc., strongly suggests that this is the case. Very difficult to think of an alternative explanation!

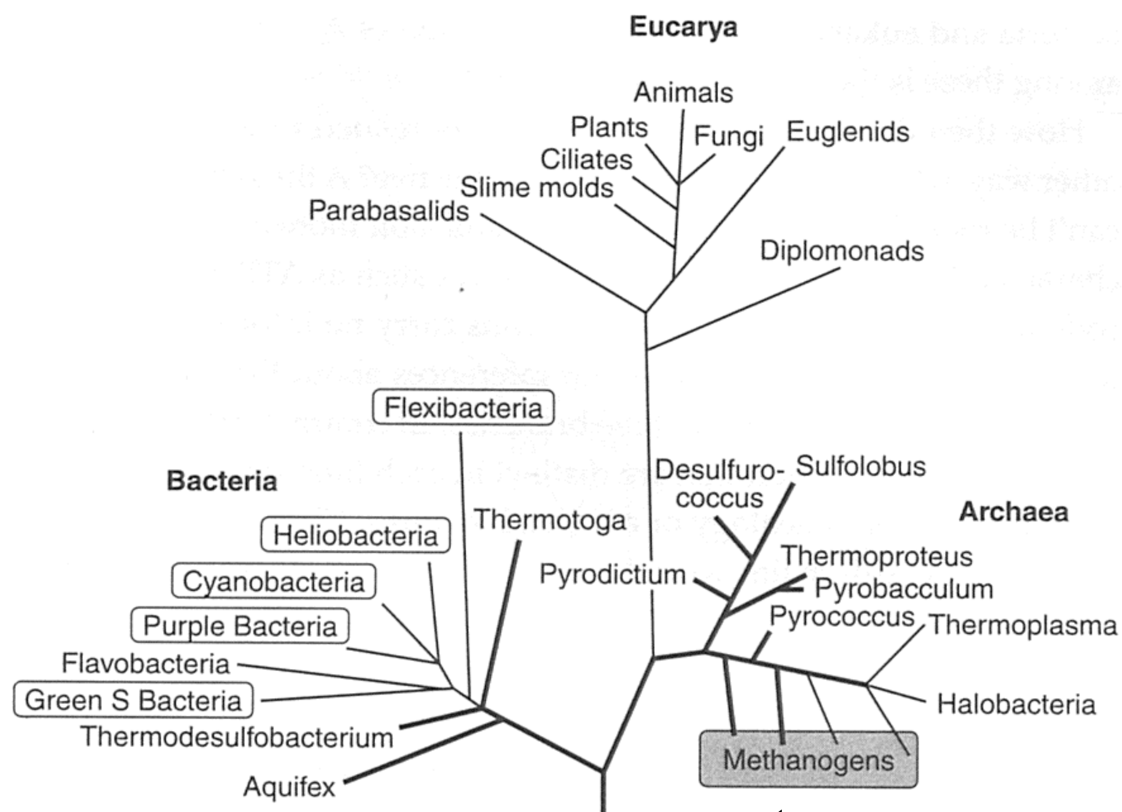
Do not confuse "last common ancestor" (LCA) with the first organism! The last common ancestor was undoubtedly some very complex proto-bacterium. It is a long way from the RNA world to the LCA!
Later you will see why many think the "root" of this tree is more like a tangled bush: **Horizontal gene transfer.**

Tree of life with thermophiles and hyperthermophiles, methanogens

The earliest microorganisms seem to have been *thermophiles and Hyperthermophiles (e.g. Thermoproteus, Thermotoga in tree to right)* , which appear near the base of most evolutionary trees.

This *might* support the idea that life began around hydrothermal vents.

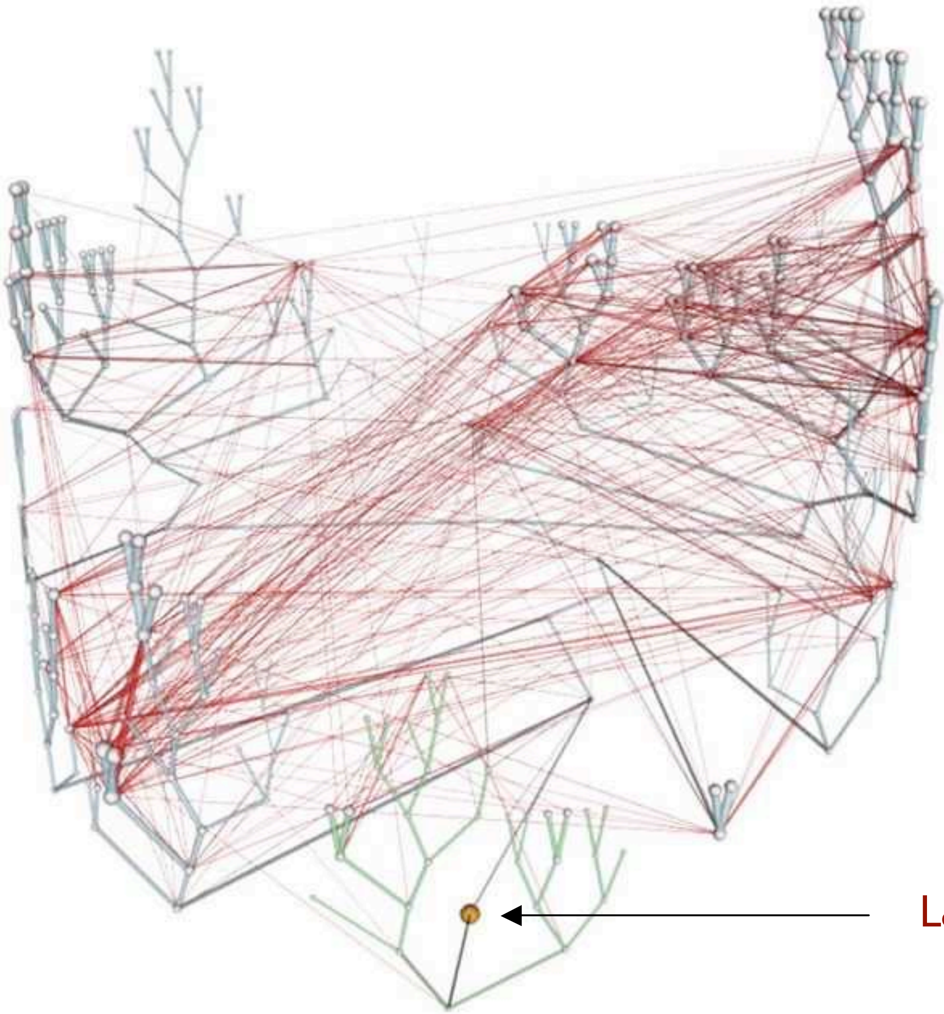
Notice that the photosynthesizing prokaryotes (names in rectangles) are bacteria, and appear to have developed significantly *later* than the thermophiles.



Photosynthesizers are in rectangles.

Hadean/Archean prokaryotes had a non-frozen world because of the methane greenhouse thanks to this class of microorganisms

Why there may be no "last common ancestor" at the "root" of the evolutionary tree:
Horizontal (or lateral) transfer of genetic material



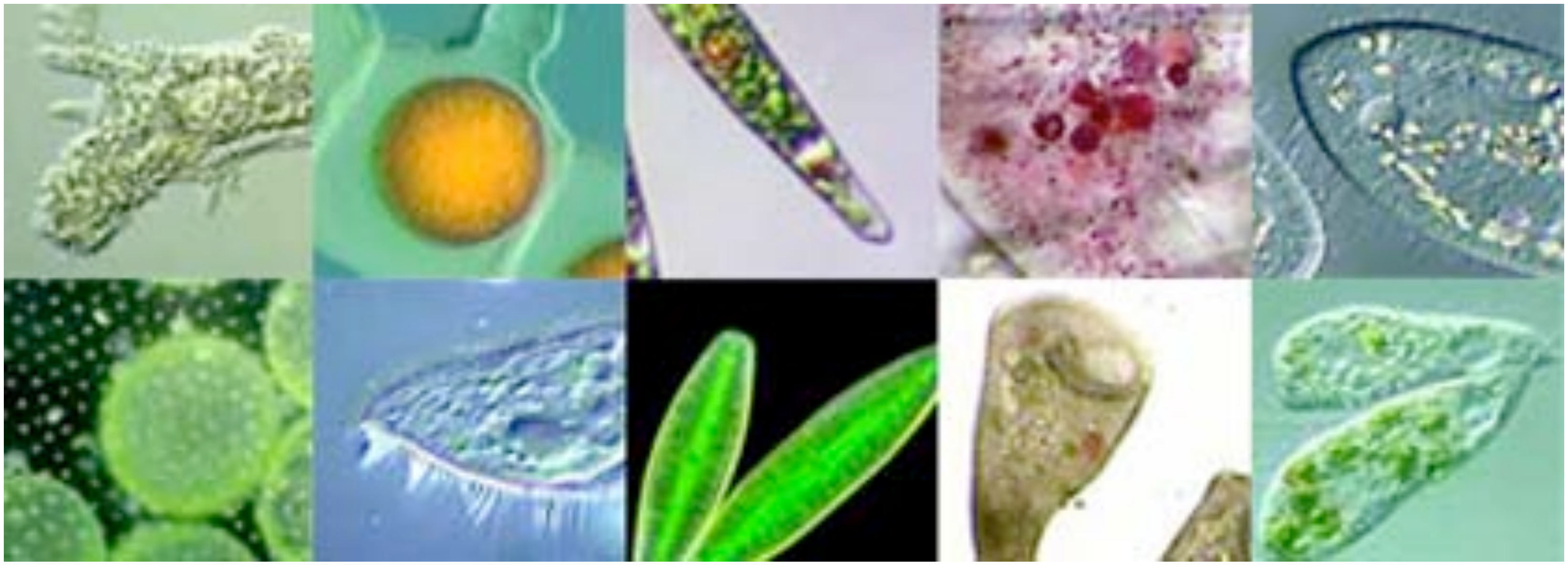
Last common ancestor?

From Ouzounis 2005

A bird's-eye view of the tree of life, showing the vines in red and the tree's branches in grey [Bacteria] and green [Archaea]. The last universal common ancestor is shown as a yellow sphere.

Eukaryotes

Eukaryotes--First extreme transition to increasing complexity (?) Or vehicle for bacterial diversification?



Eukaryotic microorganisms

We see mostly Eukaryotic life forms around us, but by far the most numerous and varied organisms (by number, species, diversity, metabolic activities, habitat, …) are the bacteria. In some ways, eukaryotes are nothing but vehicles for *bacterial symbiosis* = **endosymbiosis.**

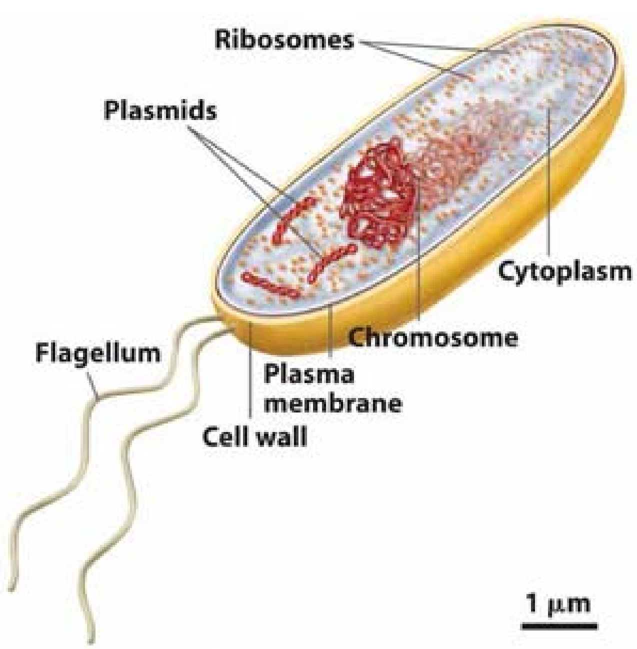
E.g. mitochondria were once free-living independent bacterial organisms.

Prokaryote-Eukaryote difference in complexity

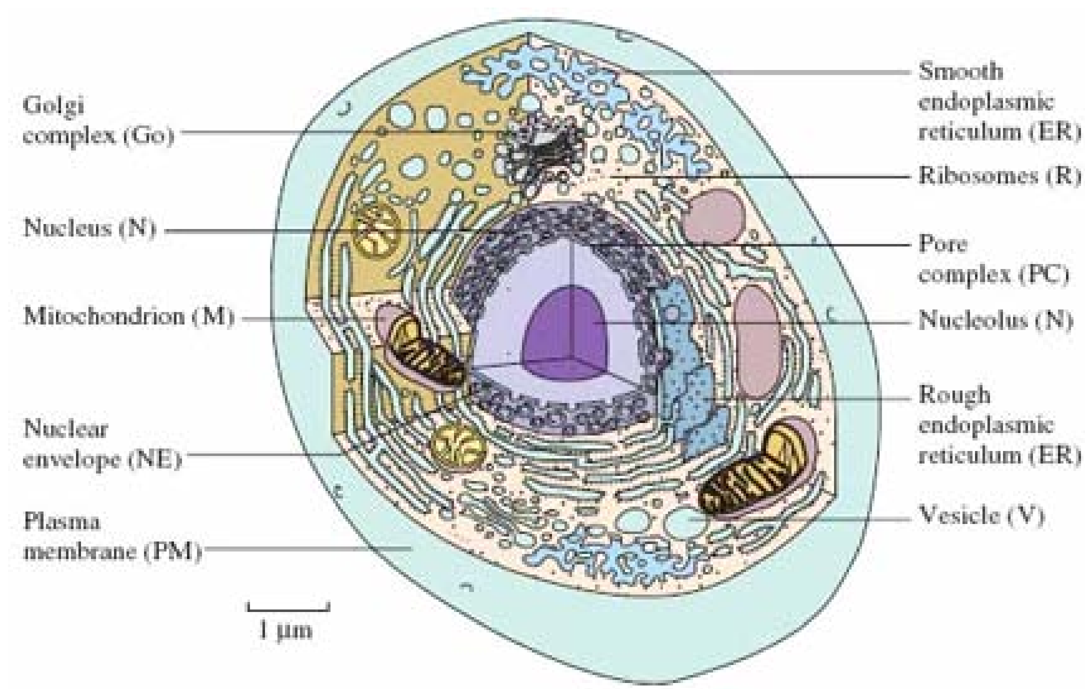
What eukaryotes have that prokaryotes don't:

1. Cell nucleus. Why would that be important?
2. Cell is *modularized* into *organelles*(e.g. chloroplasts, mitochondria, Golgi bodies, …see illustration to left). Modular structure is a great way to increase complexity.
3. Cytoskeleton: structural support but also rapid transport of chemicals within eukaryotic cells.
4. Packing of DNA: allows for *much* larger genome. Bacterial DNA is "simply" loops stored in a "nucleoid", not packed into chromosomes.

Prokaryotic cell

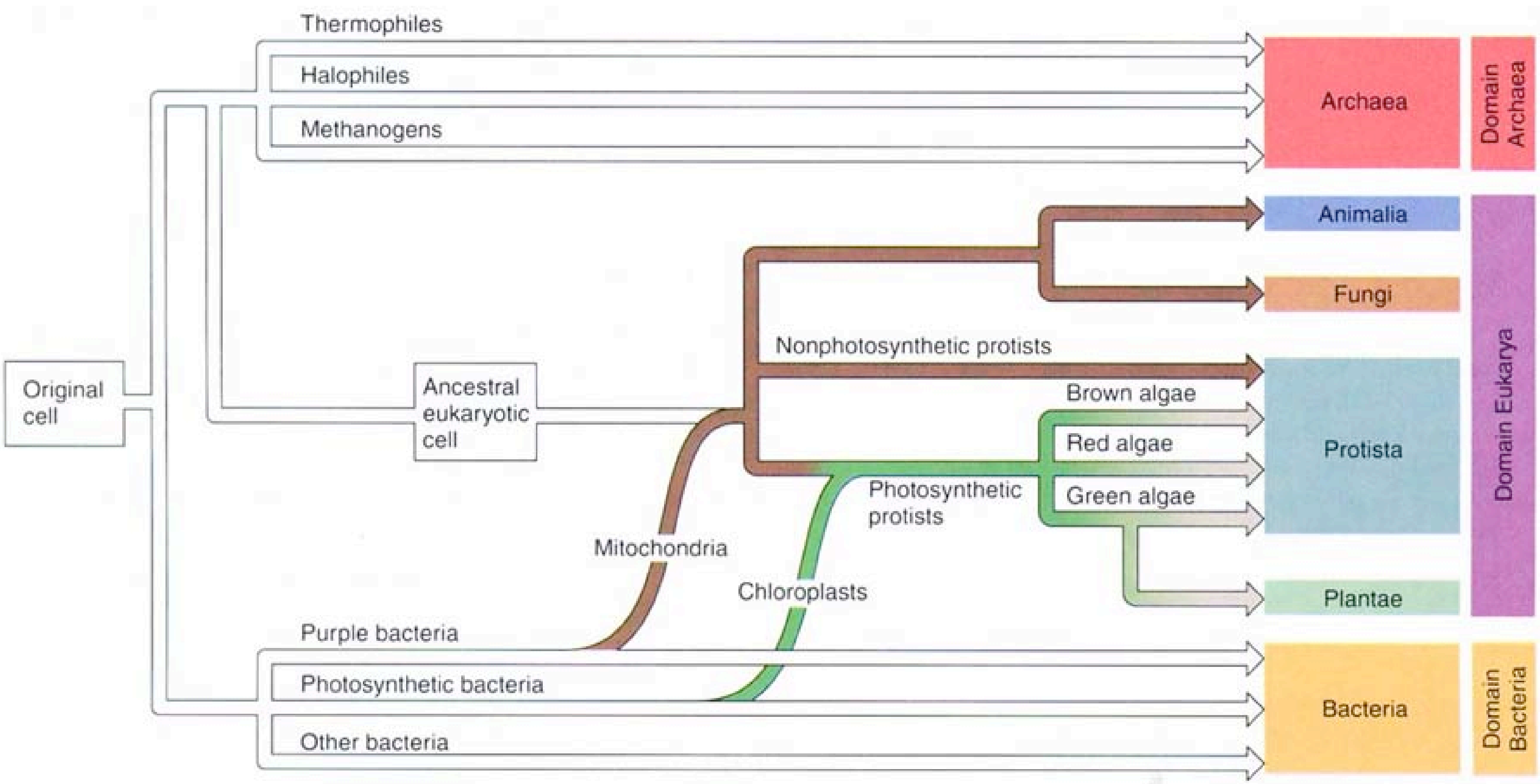


Eukaryotic (animal) cell

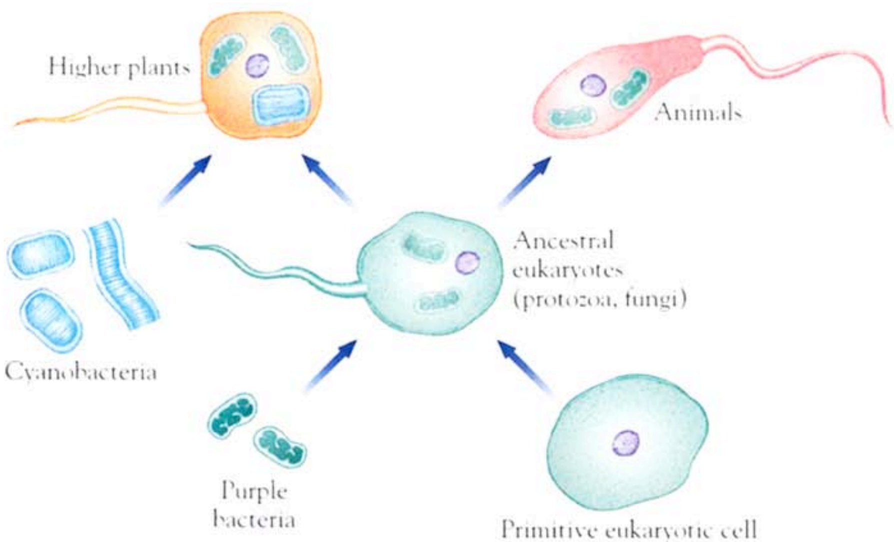


Rise of the eukaryotes

The merging of the domains indicates how *endosymbiosis* was almost certainly at work in the development of the eukaryotes.



Endosymbiotic origin of eukaryotes

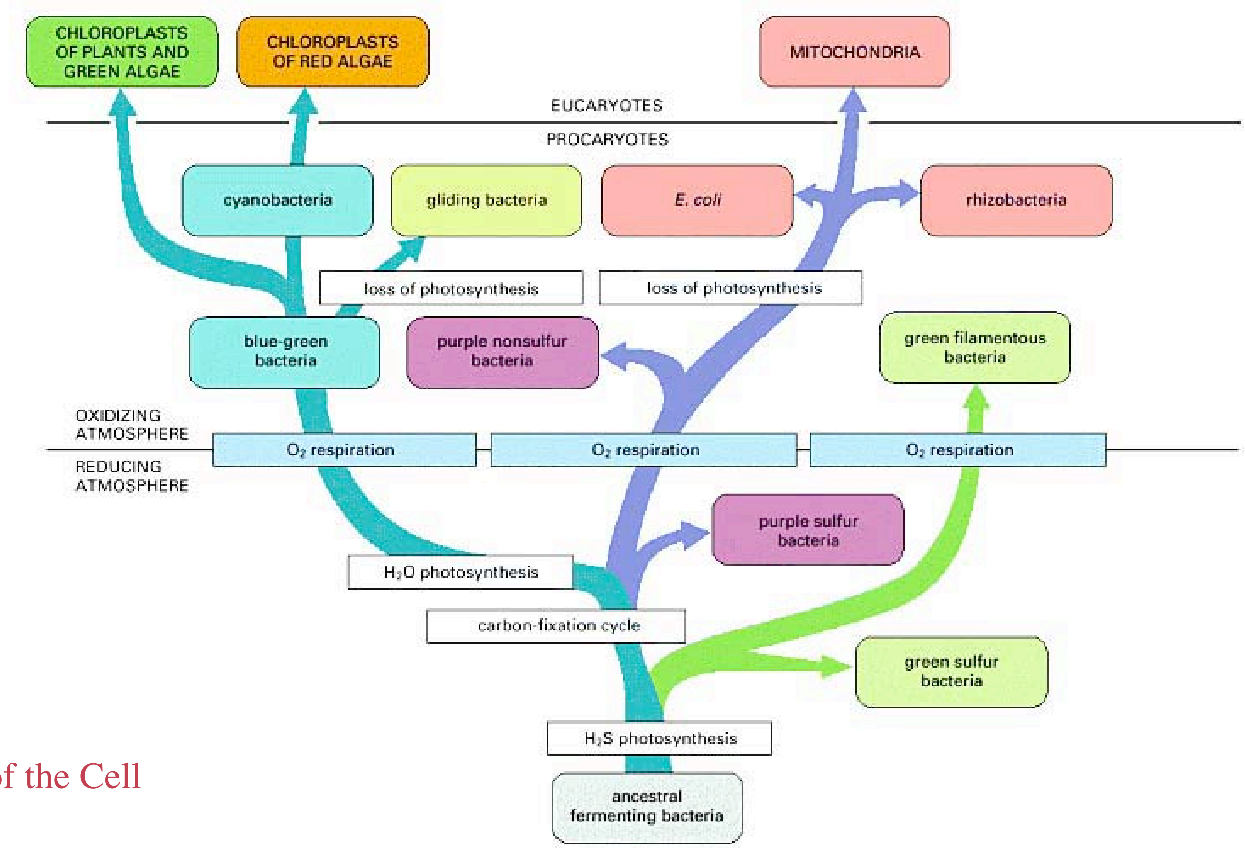


The origin-from-without, or endosymbiosis, hypothesis argues that chloroplasts and mitochondria were once free-living prokaryotic organisms that were long ago engulfed by the primitive eukaryotic cell, with cyanobacteria being the precursors of choloroplasts and purple bacteria the precursors of mitochondria. Molecular data strongly support the endosymbiosis hypothesis, although questions still remain about the number of times engulfment occurred, for both chloroplasts and mitochondria.

Study the above illustration. It emphasizes the role of symbiosis in multicellular eukaryotes from fungi to animals and plants. For purposes of discussion of communication with *complex* extraterrestrial life, notice the possible extreme **contingency** at work here: ***There would be no plants and animals unless this form of symbiosis into a modularized more complex organism occurred!*** Others would say symbiosis is so adaptive that it should be universal (i.e. **convergent**)

1. Oxygen respiration ~ 2 Gyr ago in three lines of photosynthetic bacteria;
2. Eukaryotes: Tree shows proposed evolution of mitochondria and chloroplasts

This isn't to memorize, only to see the value in seeing the relationships in this way. You should already be familiar with some of the terms in the boxes below.

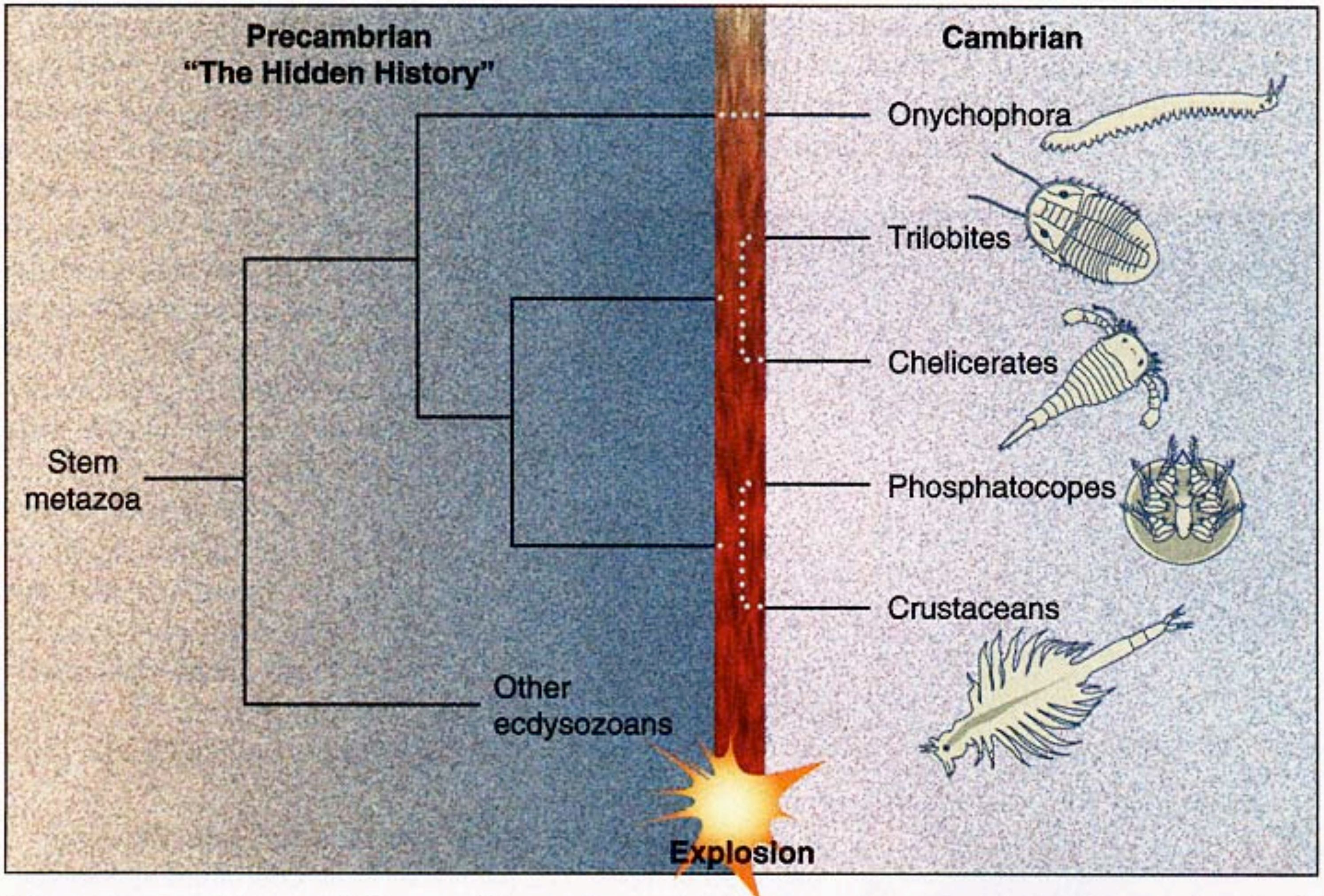


From B. Alberts,
Molecular Biology of the Cell

Figure 14-70. A phylogenetic tree of the proposed evolution of mitochondria and chloroplasts and their bacterial ancestors. Oxygen respiration is thought to have begun developing about 2×10^9 years ago. As indicated, it seems to have evolved independently in the green, purple, and blue-green (cyanobacterial) lines of photosynthetic bacteria. It is thought that an aerobic purple bacterium that had lost its ability to photosynthesize gave rise to the mitochondrion, while several different blue-green bacteria gave rise to chloroplasts. Nucleotide sequence analyses suggest that mitochondria arose from purple bacteria that resembled the rhizobacteria, agrobacteria, and rickettsias—three closely related species known to form intimate associations with present-day eucaryotic cells. Archea are not known to contain the type of photosystems described in this chapter, and they are not included here.

Cambrian Explosion--of body plans

A crucial evolutionary "event": Precambrian/Cambrian transition and the appearance of larger, more complex organisms in a short period of time



The early evolutionary history of the arthropods. The new discovery of a crustacean-like fossil (Phophatocope) in the early Cambrian pushes the branching events leading up to it and its relatives further back in time—into the Precambrian. Drawings are not to scale.

Examples of very old microfossils and modern counterparts

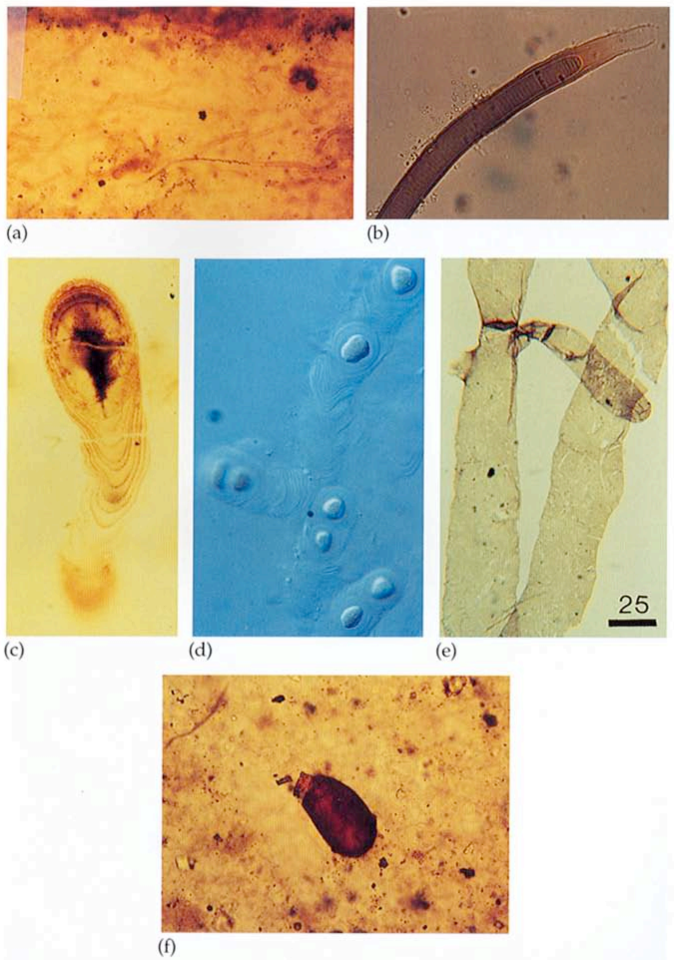


Plate 2. Fossils in Akademikerbeen cherts and shales, and some living counterparts. (a) Filamentous fossils of mat-forming microorganisms in Spitsbergen chert; each tube is about 10 microns wide. (b) The cyanobacterial genus, *Lyngbya*, which provides a modern counterpart for the fossils in a. (The specimen is 15 microns wide.) Note the extracellular sheath that surrounds the ribbon of cells. Because it is not easily destroyed by bacteria, this sheath, rather than the cells it contains, is likely to enter the fossil record. (c) *Polybessurus bipartitus*, a distinctive stalk-forming microorganism in Spitsbergen cherts; specimen

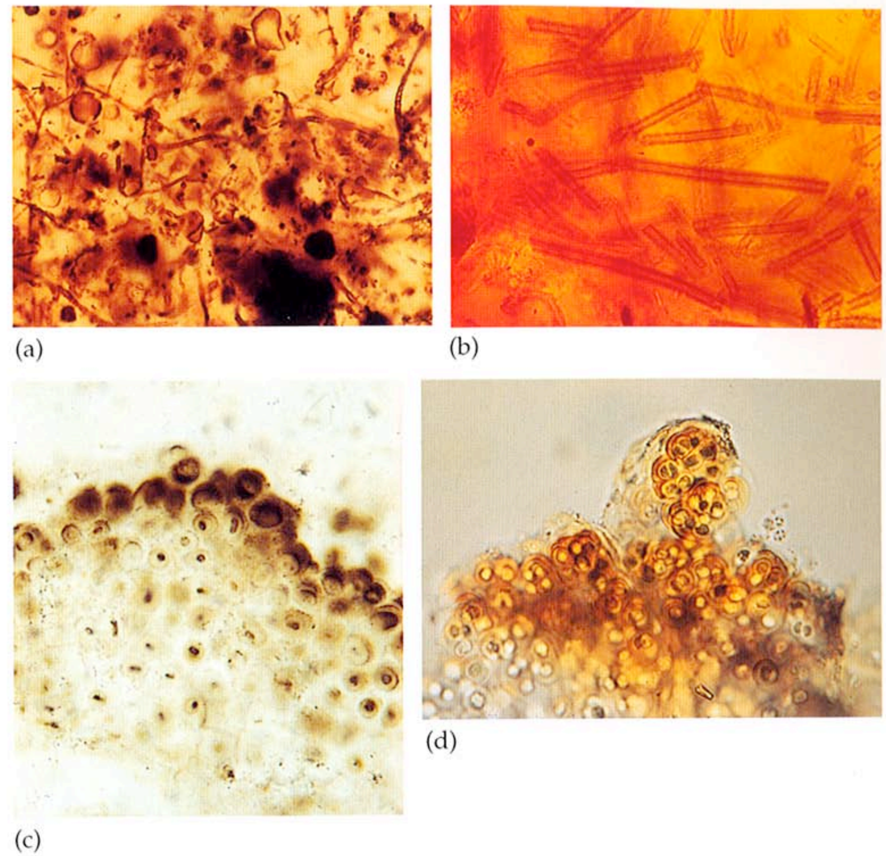


Plate 3. Early Proterozoic microfossils and their modern counterparts. (a) A microscopic view of Gunflint chert, chockablock with tiny fossils. (b) *Leptothrix*, a modern iron-loving bacterium thought to be similar to the filaments in Gunflint fossil assemblages. In both figures, the filamentous organisms are 1–2 microns across. (c) *Eoentophysalis* cyanobacteria in early Proterozoic chert from the Belcher Islands, Canada. (d) A modern *Entophysalis* species for comparison (ellipsoidal envelopes around cells are 6–10 microns wide in both illustrations). (Photo (c) courtesy of Hans Hofmann; photo (d) courtesy of John Bauld)

Cyanobacterial microfossils: Age ~ 1.5 billion years

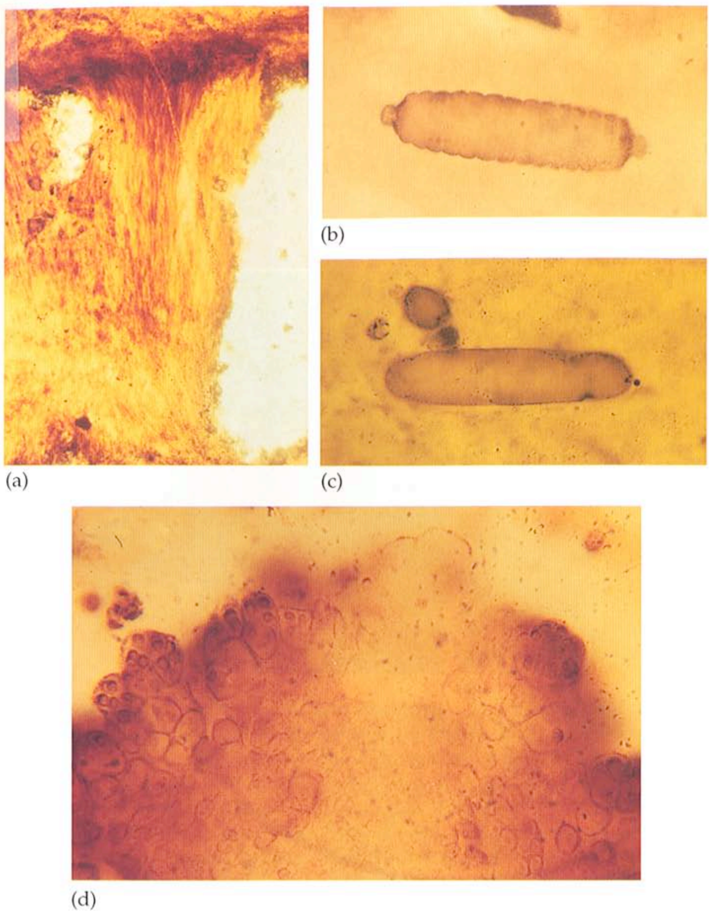


Plate 4. Cyanobacterial microfossils in cherts of the 1.5-billion-year-old Bil'yakh Group. (a) A vertical tuft of tubular filaments, preserved in this orientation by very early formation of calcium carbonate cement (each filament is about 8 microns across). (b) A filamentous cyanobacterium, showing how cells were arranged along its length; the specimen is actually preserved as a lightly pigmented cast, originally made in rapidly cemented carbonate sediment (fossil is 85 microns long).(c) *Archaeoellipsoides*, the large (80 microns long, in this case) cigar-shaped fossil interpreted as the specialized reproductive cell of an *Anabaena*-like cyanobacterium. (d) 1.5-billion-year-old mat-building colony of *Eoentophysalis*; see plate 3d for its modern counterpart.

Eukaryotic microfossils: Ages 1.5 to 0.57 billion years

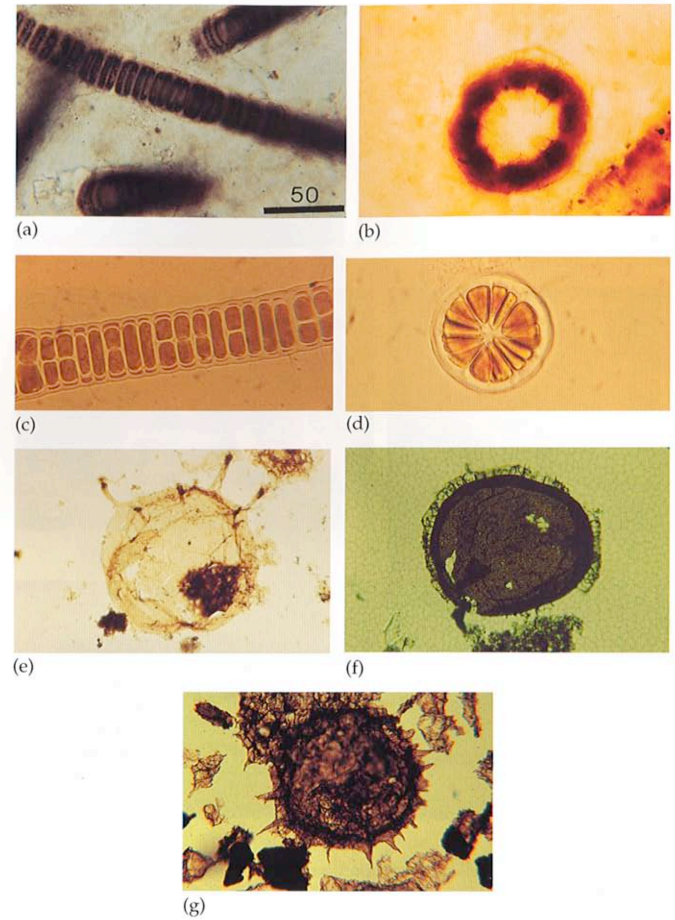
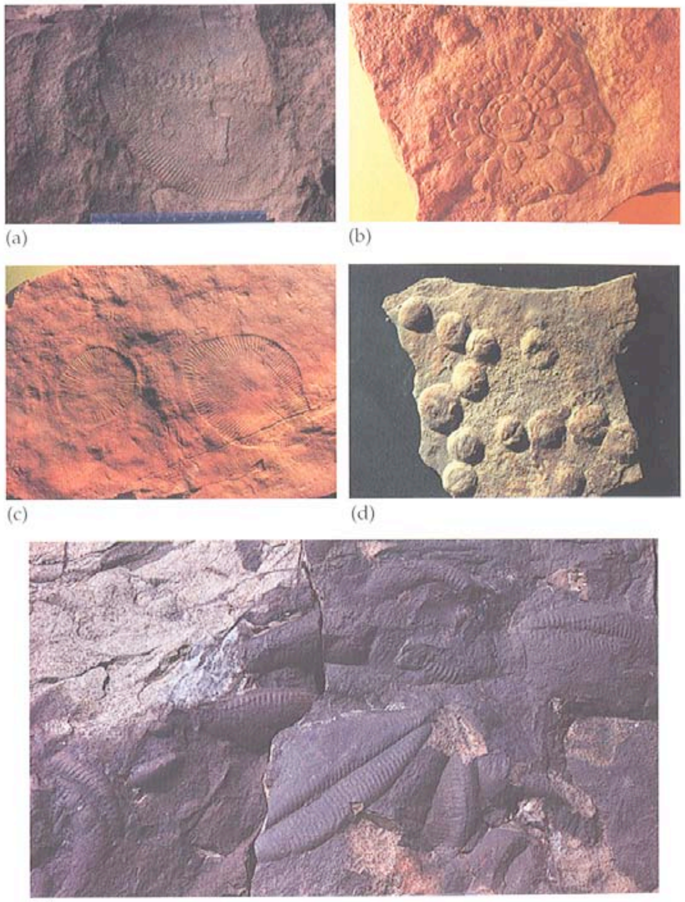


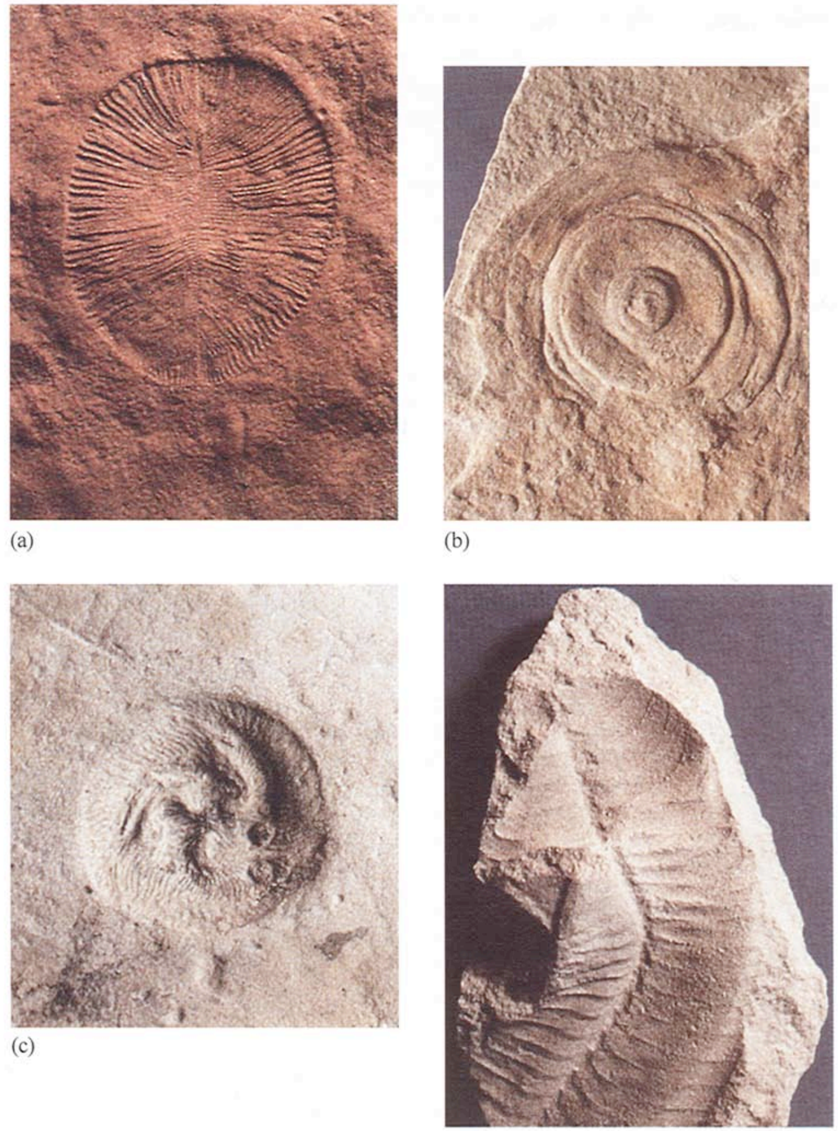
Plate 6. Fossils of Proterozoic eukaryotes. (a) and (b) illustrate the fossil *Bangiomorpha* in ca. 1.2-billion-year-old cherts from arctic Canada. (c) and (d) show the living red alga *Bangia*. All specimens are about 60 microns in cross-sectional diameter. (e) *Tappania*, a 1.5-billion-year-old microfossil from northern Australia; fossil is 120 microns wide. (f) A lavishly ornamented microfossil (200 microns in diameter) interpreted as the reproductive spores of algae from ca. 1.3-billion-year-old rocks in China. (g) A large (more than 200 microns) spiny microfossil from ca. 570–590-million-year-old rocks in Australia. (Photos (a)–(d) courtesy of Nicholas Butterfield)

Ediacaran (Precambrian/Cambrian transition) fossils



(a) (b) (c) (d) (e)

Plate 7. Ediacaran fossils from Namibia and elsewhere. (a) *Swartpuntia*, a three-winged fossil found in the uppermost Proterozoic beds of the Nama Group; only two "wings" are evident in these fossils. (b) *Mawsonites*, a 4-inch disk from South Australia, interpreted an a sea anemone–like animal or the holdfast of a sea pen–like colony. (c) *Dickinsonia*, the most celebrated (and controversial) of vendobiont fossils. This specimen is from the Ediacara Hills of South Australia. (d) *Beltanelliformis*, a spherical green alga, here seen in latest Proterozoic sandstones from the Ukraine; specimens 1/2 to 3/4 inch across. (e) *Pteridinium*, another three-winged fossil found in sandstones of the Nama Group. (Photos (b) and (c) courtesy of Richard Jenkins)



(a) (b) (c) (d)

Sudden increase in complexity after Precambrian/Cambrian transition ~ 550 Myr ago

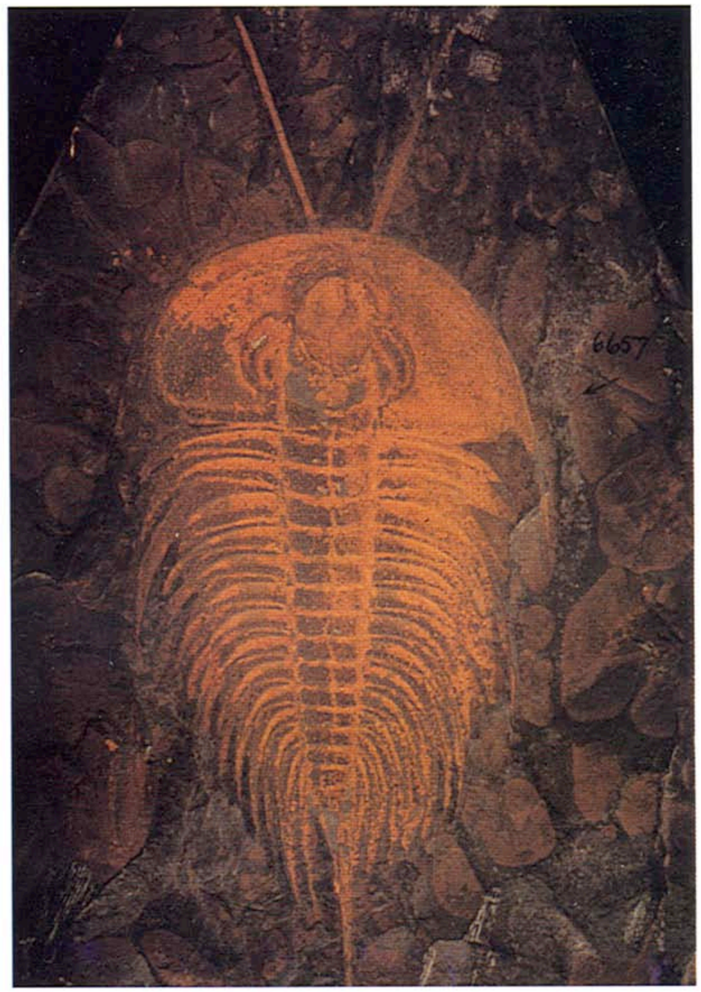


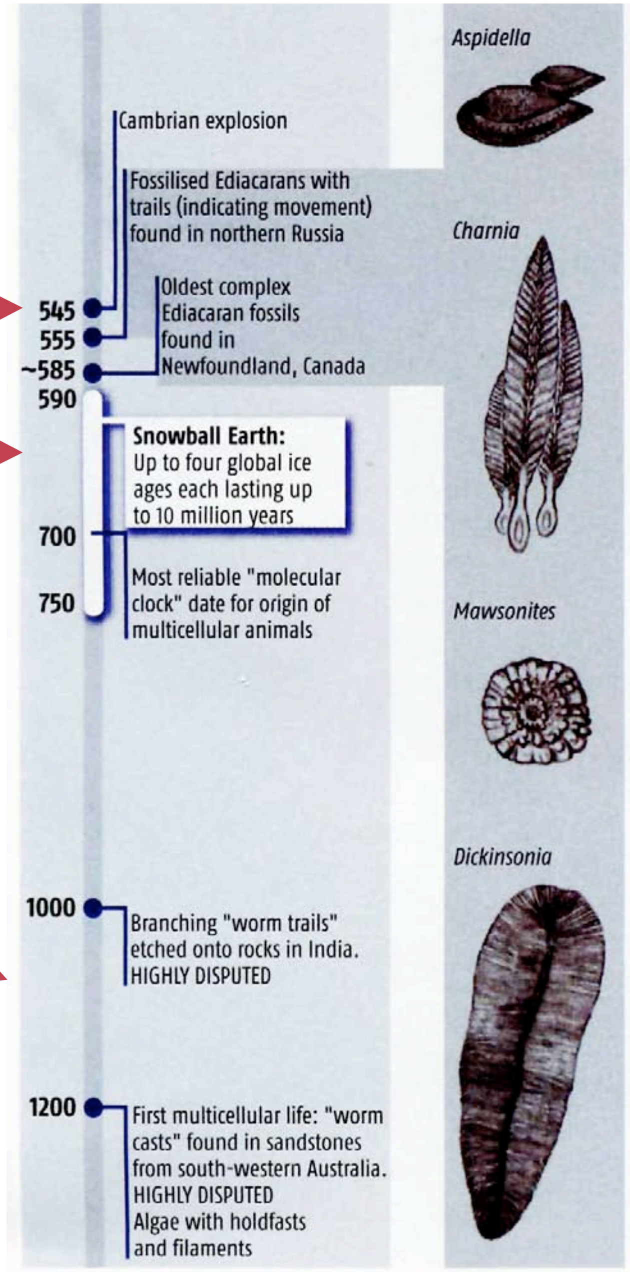
Plate 8. The trilobite *Olenellus*, illustrating the tremendous complexity achieved by Early Cambrian animals. (Photo courtesy of Bruce Lieberman)

Summary of some major events since 1200 Myr ago

Cambrian Explosion

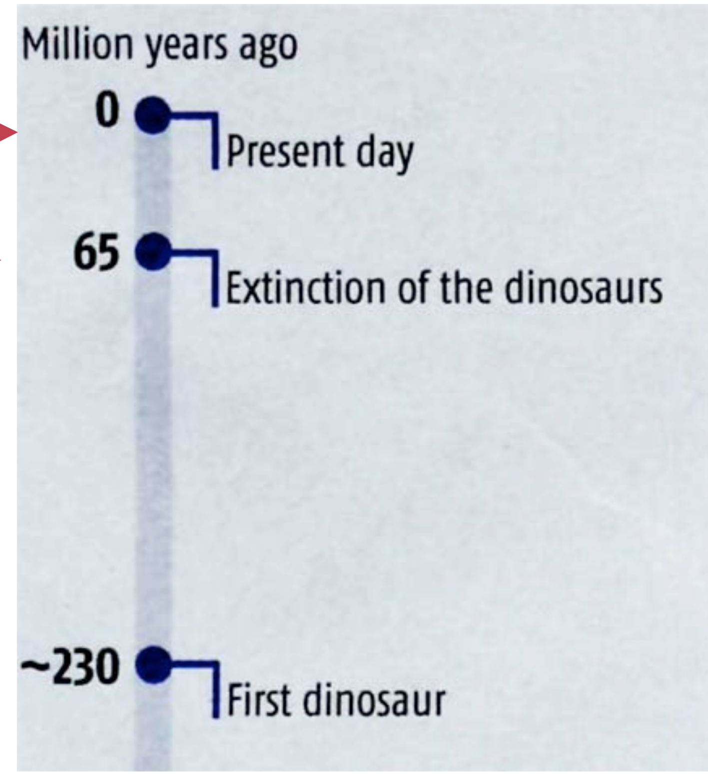
Another Snowball Earth

Meiosis?

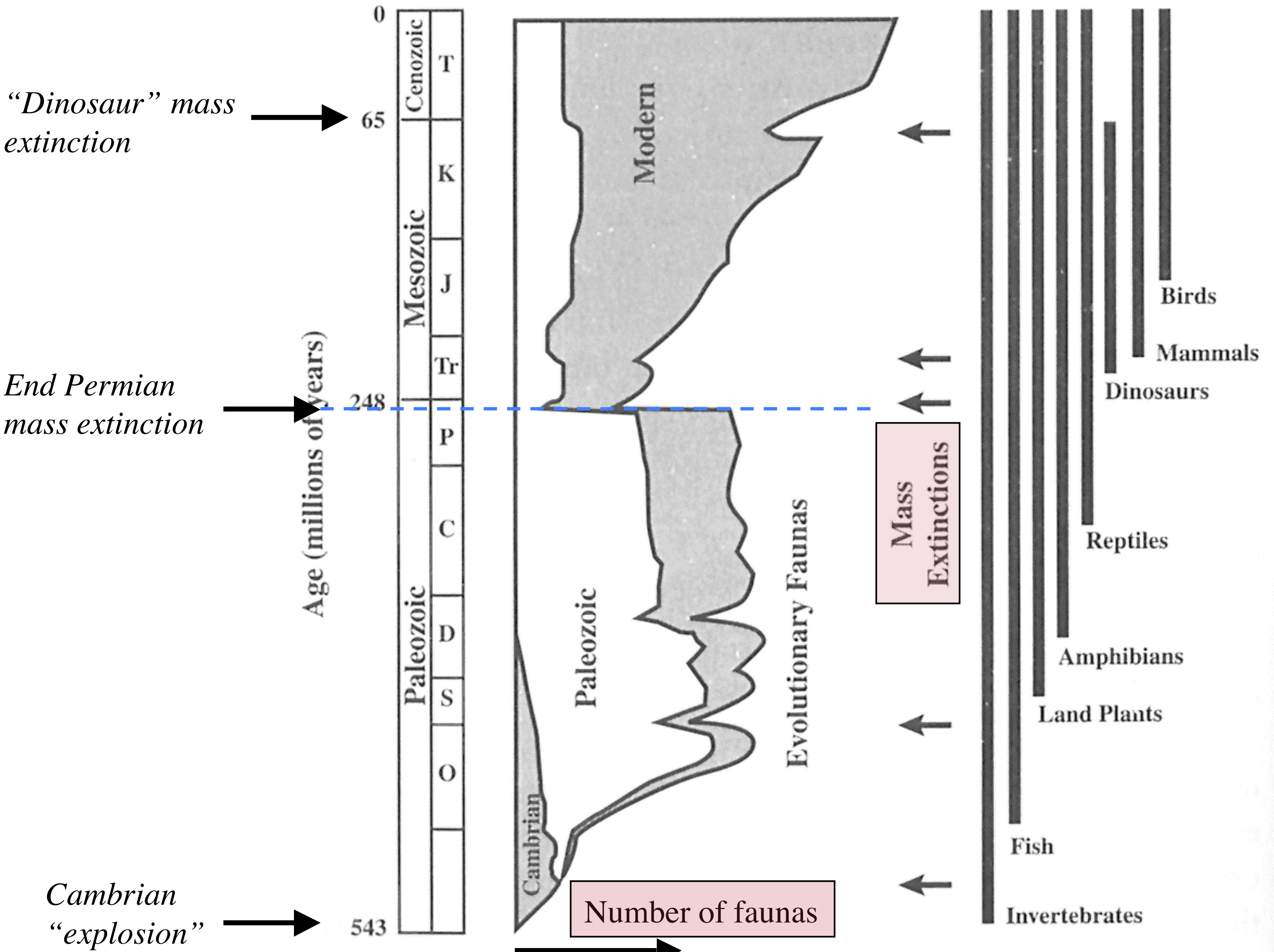


Primates

Mass extinction



Diversity continued to "explode" after the Precambrian/Cambrian transition



The diversity of multicellular organisms over the past 543 million years.

Review of major evolutionary events

- Earliest biomarkers ~ 3500 to 3800 Myr. These are not from microfossils, but from isotope ratios
- (12C/13C is the most commonly used), and characteristic hydrocarbons produced by life (e.g. keragens).
- Considered extremely uncertain. We don't really know how long it took for life to begin.

- 3-4 Gyr. **Lateral (horizontal) transfer of genetic information** between bacteria rampant. This was probably the most extensive evolutionary diversification of all time (more than Cambrian explosion)

- ***Photosynthesis***. Various sources you will encounter say about 3 Gyr, and more recent say 2.7 Gyr.
- This leaves an uncomfortable ~ 1 Gyr before the atmosphere became oxygenated--difficult to hide it in the crust for this long. Oct 2008--strong arguments that **there is *no* convincing evidence for photosynthesis earlier than 2.1 Gyr.**

- **"Oxygen holocaust"**--Atmosphere fills up with O_2 after crust saturated (~ 2 Gyr ago). Almost certainly due to advent of bacterial photosynthesis. (That is why ozone is considered a viable biomarker.)
- But this also probably made energy production more effective for eukaryotes (text)

- Oxygen wiped out methane through chemical reactions, no more greenhouse **→ *Snowball Earth***:
- complete glaciation. *But date is uncertain, so this is tentative.*

- Origin of **eukaryotes** by **endosymbiosis** (mitochondria, chloroplasts,…)--establishes "**modularity**" as major structural feature of complex design. (Fig. in text) Notice similarity in timing for atmospheric oxygen and eukaryotes.

Major evolutionary events (continued)

- **Meiotic** (sexual) reproduction--increases diversity, prevents mutational meltdown (~ 1000 Myr?), allows development of **larger genomes**?

- **Cambrian explosion** --sudden appearance of large and complex life forms (545 Myr). Without this event, no SETI!

- **Colonization of land** by plants and fungi, leading to land animals (~ 500 Myr)--no predators yet! Note importance for SETI.

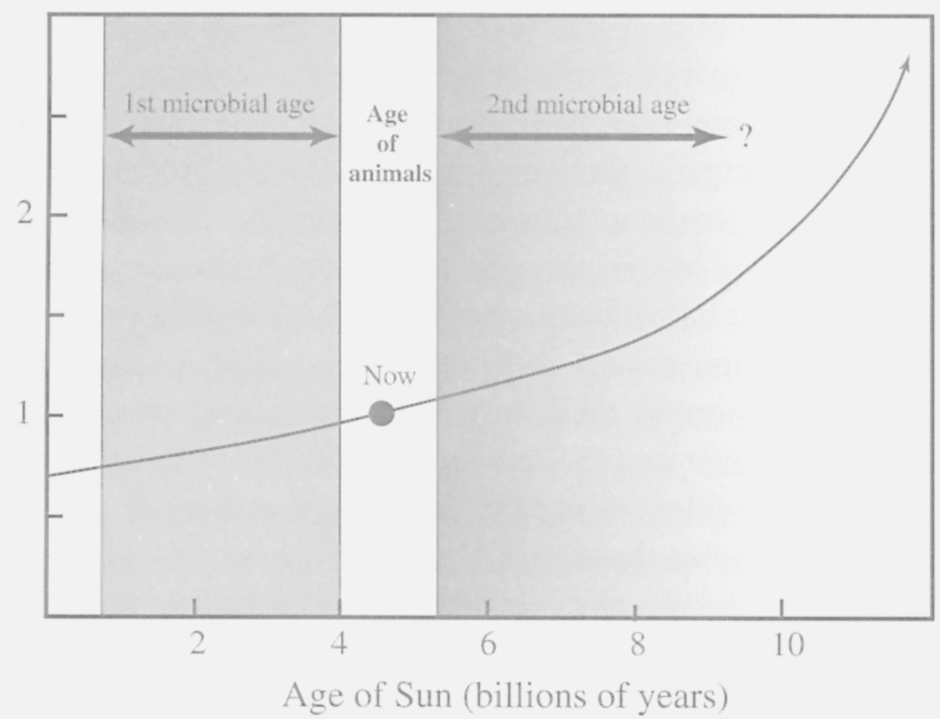
- **Mass extinctions**: several major, many minor, between ~ 500 Myr and 65 Myr (and many would say today). 65 Myr extinction ⇒ "dinosaur extinction" due to large bolide impact (also called K-T event). No mammal dominance without this? See text for good discussion.

- **Hominids** to earliest homo sapiens: 6 to 0.2 Myr (will discuss separately).
- *Probably won't get to this for Exam 4.*

Next: Convergence, then revisit mass extinctions.

The Sun's brightening could lead to a second (and final) microbial era in the future:

If duration of "animal era" is so brief, chances of communication (SETI) would be very small.



For its first 10 billion years, the Sun slowly increases in brightness. The effect is gradual but it is the major reason why Earth's biological capabilities change dramatically with time. The brief age when evolution and environmental conditions allow plants and animals to exist is bracketed by two long-duration ages when the Earth is solely inhabited by microbes invisible to the naked eye.

Convergence?

The history of life on Earth so far probably look pretty "contingent," and will look even more so from the point of view of genome evolution. So we pause to summarize a few cases for "convergence."

The* major question for SETI is: *Do we expect some or most of these developments to occur elsewhere? Was evolution "convergent" ?
We especially want to know if this is the case for complex traits like "intelligence."

- **Could point to MANY examples (see pictures to follow):**
  flight, pouches, sonar, eyes, jet propulsion, even social structures.

- **But these *could* be due to lateral transfer, in particular "*viral transduction*."**

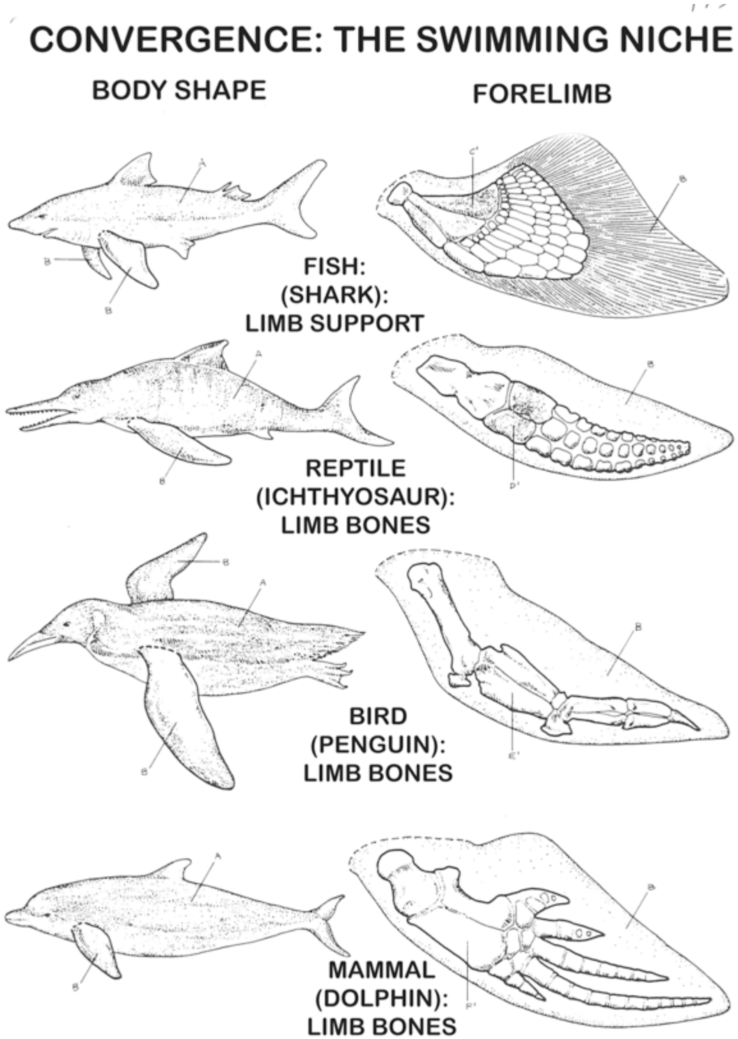
- **Also, interpreting traits is tricky because of things like *exaptation* (explained in class)**

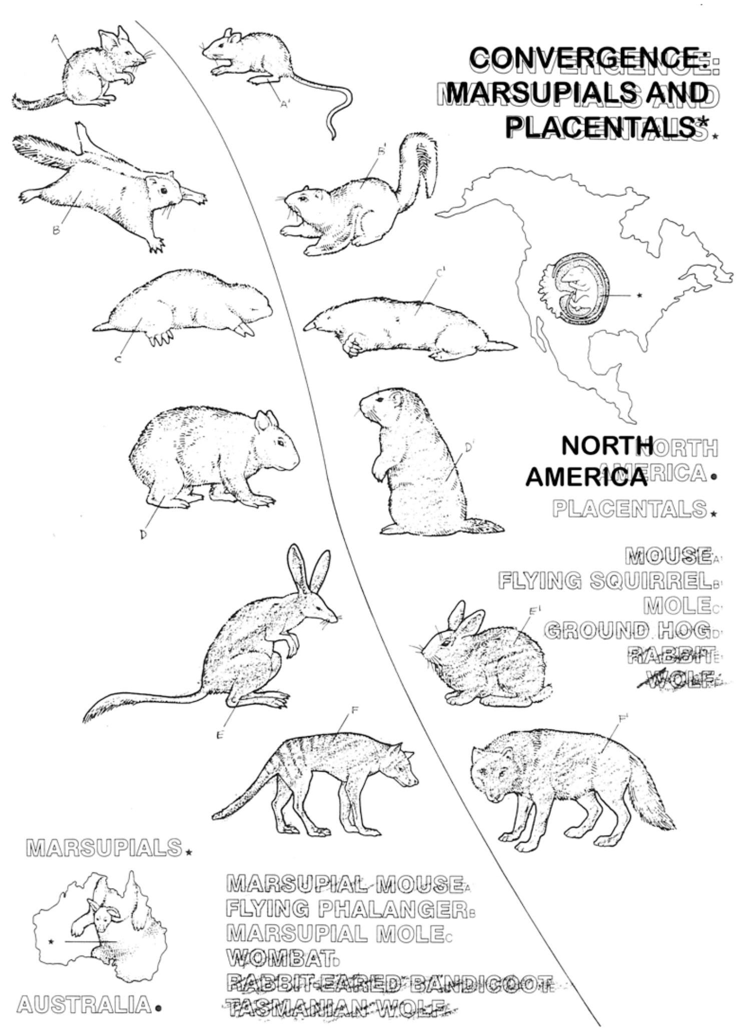
- **And *some* traits would be very useful (adaptive) but have never arisen (e.g. cellulose-digesting enzyme in animals), or have arisen only once (the case of woodpeckers will probably be discussed in class).**

- **And there are undoubtedly processes, especially environmental processes like impacts, that are completely unpredictable.**

- **We need to look at the *genome-level processes of evolution* to get any idea about whether we expect convergence to occur or not (later topic in notes).**

Examples of convergence of adaptive traits: Swimming and marsupials/placentals





Convergence: burrowing mammals

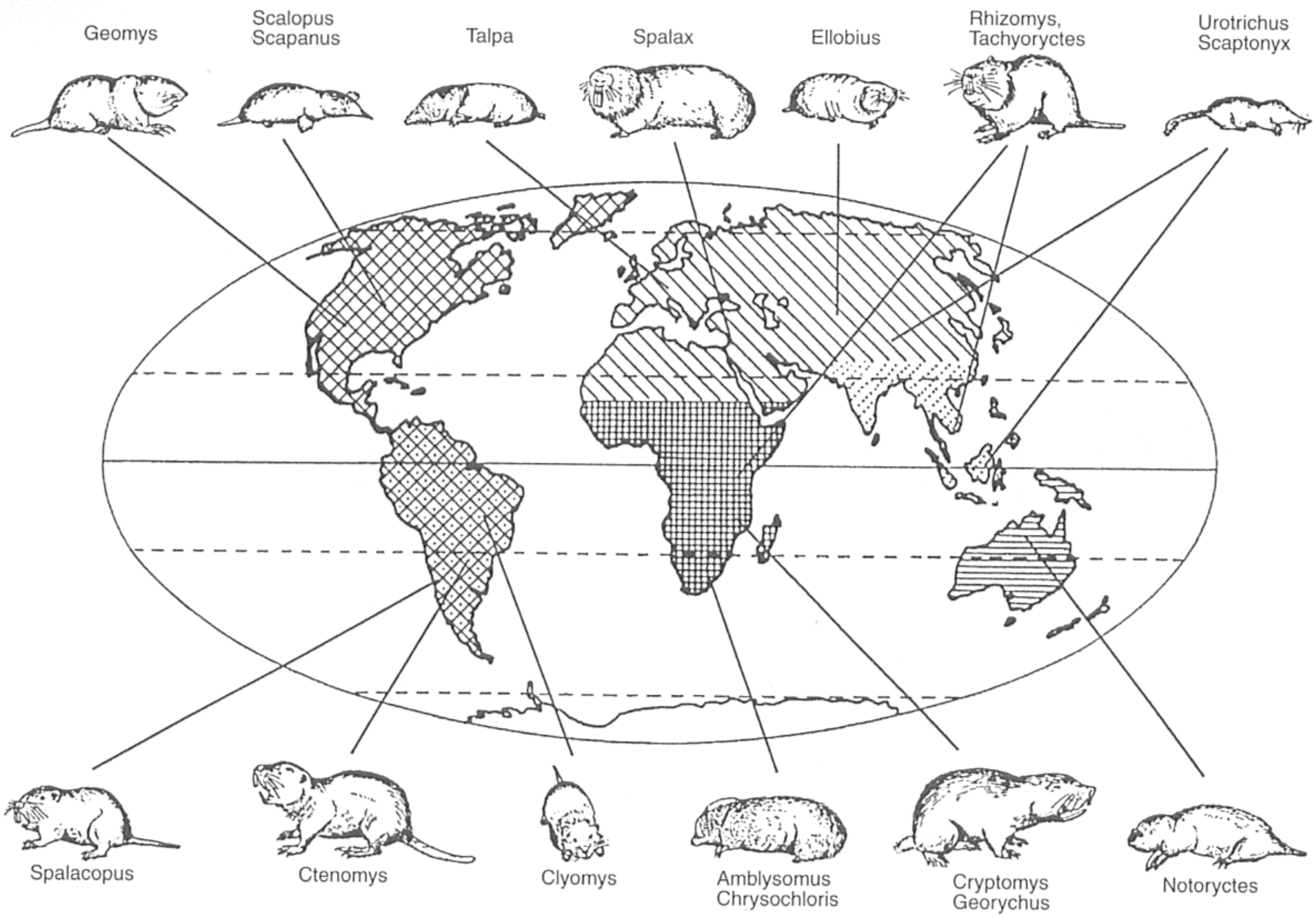
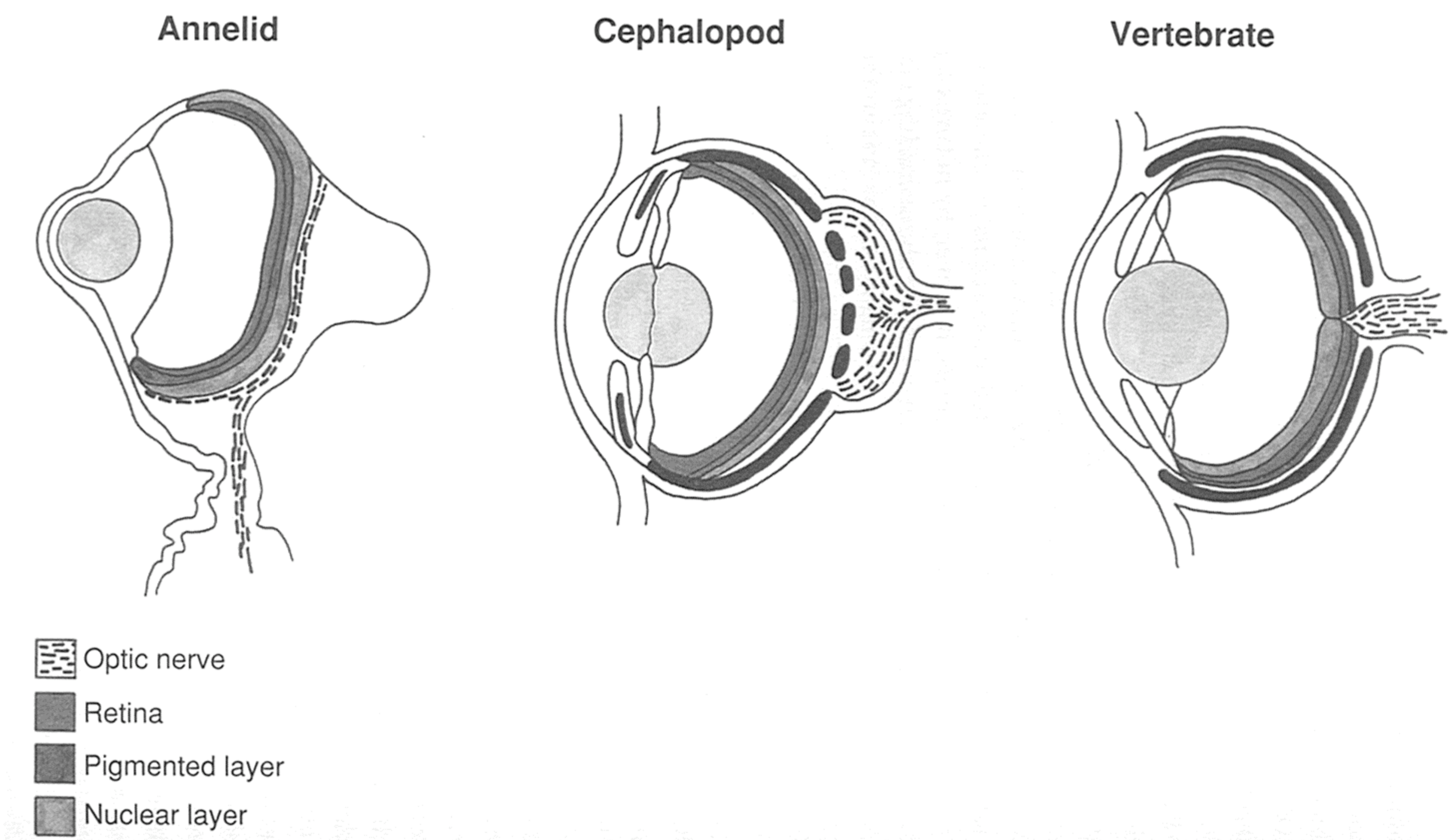


FIGURE 6.8 Convergent evolution in the burrowing (fossorial) mammals, including the familiar mole (*Talpa*), mole-rat (*Spalax*), and marsupial mole (*Notoryctes*). (Reproduced from fig. 1 of E. Nevo (1995) Mammalian evolution underground. The ecological–genetic–phenetic interfaces, *Acta Theriologica*, Supplement 3 (Ecological genetics in mammals II, eds. G. B. Hartl and J. Markowski), pp. 9–31, with permission of author and *Acta Theriologica*.)

Convergence: complex eye design



Missing great slide showing how eye plans may *not* suggest convergence…Will add later if I find it.