

Major Events in the History of Life

Ten-Part Online Course **(17 Lectures + 7 Laboratory Sessions)**

Instructor:

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Required Text:

Cradle of Life. 1999. JW Schopf. (Princeton University Press, Princeton NJ), 367 pp. [ISBN 0-691-00230-4]

Optional Texts:

Major Events in the History of Life. 1992. JW Schopf, Ed. (Jones & Bartlett, Boston MA), 190 pp. [ISBN 0-86720-268-8]

Evolution! Facts and Fallacies. 1999. JW Schopf, Ed. (Academic Press, San Diego, CA), 159pp. [ISBN 0-12-628860-7]

Evolution and the Molecular Revolution. 1999. CR Marshall and JW Schopf, Eds. (Jones & Bartlett, Boston MA), 166 pp. [ISBN 0-86720-910-0]

Grading:

Online Laboratory Sessions

Mid-term Laboratory Exam: _____	15%
Final Laboratory Exam: _____	18%
Laboratory Reports (due weekly): _____	7%

Online Lecture Material

Mid-term Lecture Exam: _____	20%
Final Lecture Exam _____	<u>40%</u>
	100%

Final Laboratory and Lecture Exams are "cumulative" (include entire course)

Median course grade (Laboratory + Lecture) will be placed at C+/B-

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OVERVIEW OF THIS COURSE

It's fair to ask why virtually all colleges and universities are subdivided into discrete, discipline-defined units -- "academic departments," in standard parlance -- when the knowledge they address is itself not constrained by such boundaries. Consider, for example, the nature of Nature. The natural world is neither entirely physical, nor wholly biological, yet academia has traditionally divided this world into two great camps -- the Physical Sciences and the Life Sciences -- populated by tribes that have such different backgrounds and divergent interests they barely speak the same language. On most college campuses, UCLA included, the tribes even occupy separate "homelands," and though their shared borders are said to be open, they actually are seldom crossed, only occasionally by foraging students, even more rarely by faculty. Each group stresses its own specialized brand of learning, and as each prods its students to master more and more about less and less, knowledge becomes increasingly fragmented.

There's little doubt that this tribalism makes things simpler for all -- learning the ropes in a single discipline is far easier than grappling with many. But it also costs, and the price is high for those exploring the real world -- which, by its nature is a dynamic interlocking mix of the physical *and* life sciences. Unlike universities, *Nature is not compartmentalized!*

By considering life on Earth from a Cosmic perspective, and using as its prime exemplar the interconnected evolutionary histories of our planet's geology, biology, and its atmosphere-ocean system, this course seeks to break down the traditional fragmented view of the natural world. In doing so, the course will (1) explore topics drawn from diverse academic disciplines -- in the *Physical Sciences*, from Physics & Astronomy, Chemistry & Biochemistry, Earth, Planetary & Space Sciences, and Atmospheric and Oceanic Science; and in the *Life Sciences*, from Cell & Molecular Biology, Microbiology & Molecular Genetics, and Organismal & Evolutionary Biology; (2) use historical (1700s) and fairly recent vignettes (e.g., NASA's 1996 announcement of "evidence of fossil life on Mars") to illustrate the humanness of scientists and how science actually is done; and (3) introduce knowledge and concepts that should be of lasting value to an educated citizen:

- ◆ the age of the solar system, of Earth, of life, and how they have been deciphered;
- ◆ the overall structure of our planet, how it formed, and how Earth compares to nearby neighbors in the solar system;
- ◆ why life is made of "starstuff" (the chemical elements CHONSP) and why these elements rather than some more exotic mix;
- ◆ how life emerged from inanimate matter, why it is made up of cells, and how the few basic kinds of living systems originated then flourished and evolved;
- ◆ why the ecosystem is structured into eaters and eatees and is made up of air-breathers and forms of life for which oxygen is a deadly poison;
- ◆ how heredity operates, what its roots are, and why it took so long for sexual reproduction to rise to prominence;
- ◆ how evolution actually works, how its workings have been discovered, and how evolution itself evolved over the geological past;
- ◆ how and when life arose on land, and why seed plants and backboned animals (dinosaurs, mammals) rose to dominate the land environment;
- ◆ how humans fit it, and how what we call intelligence is actually rooted very deeply in the Universal Tree of Life.

Major Events in the History of Life

NOTES REGARDING THIS COURSE

It will help you -- immeasurably -- to read the lecture outline in this Syllabus for each and every lecture **before you view the online presentation**. The key points of each lecture are highlighted and the new technical terms are defined.

Be sure also to read the assigned reading in *Cradle of Life*. **You will actually enjoy it!** It is not overly technical. It was written at a level that you can understand; it has lots of pictures; and parts of it read like a novel with some really good stories, for example:

- The visit to UCLA of the world famous origin-of-life scientist A.I. Oparin;
- A once-in-a-lifetime sojourn to the home of the surrealist painter Salvador Dalí;
- The preserved bones of one of the "sinful ones" buried in the 40 days and 40 nights of the Biblical Noachian flood;
- The greatest fraud in the history of natural science, dating from 1725; and
- The "real story" of NASA's 1996 claim of the discovery of past life on Mars. (Moreover, questions from the assigned readings are likely to be on the mid-term and final lecture exams.)

This is a broadly interdisciplinary course, including material from diverse fields of understanding -- geology, biology, paleontology, atmospheric science, comparative planetology, evolution, and even aspects of the history of science and how science is done. It is intended to be interesting and educational, a course that will give you a basic understanding of life's long history on Earth and that will introduce knowledge and concepts of lasting value to an educated citizen. Above all, this course should be enjoyable -- it should be good fun!

WEEKLY SYLLABUS

LECTURE 1 -- EARTH SCIENCE: ROCKS, MINERALS, AND GEOLOGIC TIME

LECTURE 2 -- BIOLOGY PAST AND PRESENT: HOW DO CELLS WORK?

LAB 1: THE NATURE OF GEOLOGIC TIME

LECTURE 3 -- HOW DOES EVOLUTION WORK?

LECTURE 4 -- BEATING THE ODDS: HOW FOSSILS ARE PRESERVED

LAB 2: FOSSILS AND THEIR PRESERVATION

LECTURE 5 -- HOW DID LIFE GET STARTED?

LECTURE 6 -- ORIGINS OF THE GLOBAL ECOSYSTEM

LAB 3: WHAT WAS THE EARLY ENVIRONMENT LIKE?

LECTURE 7 -- THE OLDEST RECORDS OF LIFE

LECTURE 8 -- EARTH'S OLDEST LIVING FOSSILS

LAB 4: PRECAMBRIAN LIFE

LECTURE 9 -- LIFE LIKE US HAS CELLS LIKE OURS

MID-TERM LAB EXAM

MID-TERM LECTURE EXAM

LECTURE 10 -- PLANTS CONQUER THE LAND

LECTURE 11 -- FROM SPORE PLANTS TO SEEDS AND FLOWERS

LAB 5: PLANTS CONQUER THE LAND

LECTURE 12 -- HOW PLANTS CHANGED THE PLANET: AN OVERVIEW

LECTURE 13 -- "SEA SHELLS" AND THEIR KIN

LAB 6: ANIMALS WITHOUT BACKBONES

LECTURE 14 -- THE LINEAGE LEADING TO HUMANS

LECTURE 15 -- BACKBONED ANIMALS TAKE OVER THE EARTH

LAB 7: BACKBONED ANIMALS LIKE US

LECTURE 16 -- TAKE-HOME LESSONS ABOUT THE HISTORY OF LIFE

LECTURE 17 -- HOW IS SCIENCE DONE?

FINAL LAB EXAM

FINAL LECTURE EXAM

LAB 1: THE NATURE OF GEOLOGIC TIME

LECTURE 1 -- EARTH SCIENCE: ROCKS, MINERALS, AND GEOLOGIC TIME

- ◆ **Minerals** (defined chemical composition, crystal form) make up rocks
- ◆ **Types of rocks** (e.g., sandstone, shale, limestone) and the **geologic cycle**
- ◆ **Principle of Superposition and relative geologic ages**, index fossils
- ◆ **Absolute geologic ages** (from decay of radioactive isotopes)
- ◆ **Geologic time**, from oldest to youngest: **Eons** (Precambrian, Phanerozoic); **Eras** (Archean and Proterozoic; Paleozoic, Mesozoic, and Cenozoic); geologic **Periods** (Vendian = Ediacaran; Cambrian, Ordovician, Silurian, Carboniferous (= Mississippian and Pennsylvanian), Permian, Triassic, Jurassic, Cretaceous, Tertiary, and Quaternary)
- ◆ **Age of Earth and solar system** (Moon, meteorites, Mars, etc.)

READING: See geologic time scale in Laboratory Manual!; *Cradle of Life*

-- **geologic time:** Prologue (pp. xi-xiv); Chpt. 1 (pp. 3-13)

OPTIONAL READING: *Evolution! Facts and Fallacies* -- **dating geologic events:** Chpt. 2 (pp. 15-36)

Technical Terms

- Cenozoic Era** _____ 65 Ma ago to present (*Age of Mammals and Flowering Plants*)
- index fossil** _____ fossil distinctive of a particular segment of geologic time
- Ga** _____ *giga anna*, one billion years (1×10^9 yr)
- Ma** _____ *mega anna*, one million years (1×10^6 yr)
- Mesozoic Era** _____ 250 to 65 Ma ago (*Age of Reptiles and Naked Seed Plants*)
- Paleozoic Era** _____ 550 Ma to 250 Ma ago (*Age of Animals Without Backbones and Spore Plants*)
- Phanerozoic Eon** _____ 550 Ma ago to present (*Age of Ecologically Specialized Megascopic Life*)
- Precambrian Eon** _____ formation of Earth (4,500 Ma ago) to 550 Ma ago (*Age of Ecologically Generalized Microscopic Life*)
- Superposition** _____ "overlying"; in a sequence of (undeformed) sedimentary rocks, "older below, younger above"

MINERALS AND ROCKS

Atoms/Molecules -----> Minerals -----> Rocks

the **MINERAL** makes up the **ROCK**

Quartz [SiO_2] -----> -----> Sandstone

Calcite [CaCO_3] -----> -----> Limestone

Dolomite [$\text{Ca,Mg}(\text{CO}_3)_2$] -----> -----> Dolostone

THE GEOLOGIC CYCLE

<u>Igneous Rocks</u>	<u>Sedimentary Rocks</u>	<u>Metamorphic Rocks</u>
Granite [WEATHERING and -----> AND ----->	Sandstone --> [HEAT ----->	Quartzite
Basalt [TRANSPORT]	Shale -----> AND ----->	Slate
	Limestone --> PRESSURE] -->	Marble
Igneous -->	Sedimentary -->	Metamorphic -->
	Igneous -->	Sedimentary -->
		Metamorphic --> etc.

NAMING OF GEOLOGIC UNITS

SUPERGROUP (two or more groups)

Group (two or more formations)

Formation (mappable rock unit)

Member (distinctive part of formation)

LOS ANGELES SUPERGROUP

Santa Monica Group

Pacific Formation

Ocean Sandstone Formation

Westwood Group

Wilshire Quartzite Formation

Hilgard Formation

Westholme Pyritic Shale Member

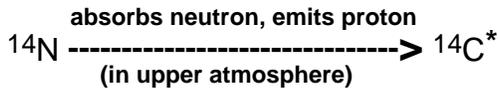
RELATIVE AGE DETERMINATION

- ◆ "Law of Superposition" (oldest stratum at bottom)
- ◆ Fossils yield *relative* ages (earlier evolved organisms below, later evolved above).
- ◆ "Index Fossil": distinctive, widespread fossil genus or species having a well defined (and usually relatively restricted) time range. For example: **the trilobite genus *Phacops*** is a Devonian index fossil (originated near beginning of Devonian geologic Period, became extinct at end of Devonian Period), whereas **trilobites in general** are Paleozoic index fossils (originated at beginning of Paleozoic Era, became extinct at end of Paleozoic Era)

ABSOLUTE AGE DETERMINATION

(1) Carbon has three isotopic forms (three types of carbon atoms, differentiated by their subatomic structure): ^{12}C , ^{13}C , $^{14}\text{C}^*$.

(2) $^{14}\text{C}^*$ is radioactive (*), formed in the upper atmosphere by interaction of cosmic rays and nitrogen atoms:



(3) $^{14}\text{C}^*$ is naturally unstable (it decays radioactively), giving off a "beta" particle (β) to revert to stable nitrogen, ^{14}N :



(4) The radioactive decay of $^{14}\text{C}^*$ to form ^{14}N occurs at a known, constant, average rate: in 5,730 years, 1.0 g of $^{14}\text{C}^*$ will decay to produce 0.5 g of ^{14}N , leaving 0.5 g of $^{14}\text{C}^*$ unchanged. After an additional 5,730 years, the remaining 0.5 g of $^{14}\text{C}^*$ will decay to produce 0.25 g of ^{14}N , leaving 0.25 g of $^{14}\text{C}^*$ unchanged. And so on. Thus, the "**half-life**" of $^{14}\text{C}^*$ is 5,730 years.

(5) By measuring in a carbon-containing fossil (e.g., a fossil bone) the amount of original ("parent") $^{14}\text{C}^*$ still remaining, and the amount of ^{14}N "daughter product" that has been produced, the absolute age of the fossil can be calculated. However, after about 10 half-lives, there will be too little $^{14}\text{C}^*$ remaining to be measured. Thus, ^{14}C -dating can be used only to date fossils that are less than about 10 half-lives in age (i.e., materials younger than about 50,000 to 60,000 years).

(6) Isotopic parent-daughter pairs, having *much longer* half-lives and occurring in *minerals* (rather than in organic matter) are used to date *rocks* of older age (viz., dating the time that the minerals in a rock were formed, for example, the time when a volcanic lava solidified). Commonly used isotopic pairs include:

Potassium -----> Argon

Uranium -----> Lead

Samarium -----> Neodymium

Rubidium -----> Strontium

Thorium -----> Lead

LECTURE 2 -- BIOLOGY, PAST AND PRESENT: HOW DO CELLS WORK?

- ◆ **What is a fossil?** -- evidence of pre-existent life, whether **morphological** (e.g., a *trace fossil*: tracks, trails, burrows; or a *body fossil*: shells, leaves, bones) or **chemical** (amino acids, chlorophylls, carbon isotopes)
- ◆ **Kinds of paleontologists** -- horizontalists, verticalists
- ◆ **Kinds of fossils that they study**-- protists: micropaleontologists, plants: paleobotanists, animals: invertebrate and vertebrate paleontologists
- ◆ **How cells work** -- DNA; protein synthesis (DNA to ribosomes to enzyme-governed metabolism); mutations
- ◆ **Universals of life** -- CHON(SP), monomers, polymers, metabolism
- ◆ **Kinds of cells** (prokaryotes, eukaryotes) and the **Domains of life** domains of life (Bacteria, Archaea, Eucarya)
- ◆ **The Universal Tree of Life** -- rRNA phylogeny

READING: *Cradle of Life* -- **biology basics:** Chpt. 4 (pp. 101-108); **ecosystems:** Chpt. 5 (pp. 143-150)

OPTIONAL READING: *Evolution and the Molecular Revolution* -- **origin of the genetic code:** Chpt. 2 (pp. 31-52)

KINDS OF PALEOBIOLOGISTS:

"VERTICALISTS" _____	life/environment through time ("vertically")
"HORIZONTALISTS" _____	life/environment through space ("horizontally")
MICROPALAEONTOLOGISTS _____	shelled protists (diatoms, radiolarians, foraminiferans) and pollen and spores
PALEOBOTANISTS _____	fossil algae, fungi, and higher plants
INVERTEBRATE _____	animals without backbones (snails, PALEONTOLOGISTS clams, sponges, trilobites, corals, etc.)
VERTEBRATE _____	backboned animals (dinosaurs, birds, PALEONTOLOGISTS fish, mammals)
PRECAMBRIAN _____	stromatolites and microorganisms
PALEOBIOLOGISTS _____	of the Precambrian Eon

Technical Terms

Archaea _____	1 of 3 rRNA domains of life, composed of archaeal prokaryotes
Bacteria _____	1 of 3 rRNA domains of life, composed of bacterial prokaryotes
CHON(SP) _____	carbon, hydrogen, oxygen, nitrogen (sulfur, phosphorus)
DNA _____	deoxyribonucleic acid, genetic material of cells
domain _____	superkingdom-like category of biologic systems
endosymbiosis _____	the living of one kind of organism within cells of another
enzyme _____	biochemical that governs and speeds chemical reactions in cells
Eucarya _____	1 of 3 three rRNA domains of life, composed of eukaryotes

eukaryote _____ organism (protist, plant, fungus, animal) having nucleated cells
horizontalist _____ specialist on life and environment of a particular geologic time
metabolism _____ the buildup or breakdown of biochemicals in cells
monomers _____ small "building block" compounds that link to make up polymers
mutation _____ change in the genetic material (DNA) of cells
polymers _____ large compounds composed of monomeric subunits
prokaryote _____ organism (bacterium, archaean) having cells that lack a nucleus
protein _____ polymer made up of amino acids
ribosomes _____ minute intracellular structures where proteins are made
rRNA _____ RNA (ribonucleic acid) present in protein-making ribosomes
verticalist _____ specialist on changes of life and environment over time

LAB 2: FOSSILS AND THEIR PRESERVATION

LECTURE 3 -- HOW DOES EVOLUTION WORK?

- ◆ **Why is a chicken like a man?** -- and why is a fish embryo like a human's? *all* life is interrelated by evolution!
- ◆ **Charles Darwin, his life and times** -- Darwin's finches, Darwin's home, the Darwinian controversy
- ◆ **Biologic species** (genetic definition: interbreeding, reproductively isolated, populations) vs. **paleontologic species** (morphologic definition: *presumed to be* interbreeding, reproductively isolated, populations)
- ◆ **How Darwinian evolution works** -- survival of the fittest *specialists*, descent with modification
- ◆ **Darwin's Dilemma** -- the "missing" early record of life; history of paleontology and the birth of Precambrian paleobiology, a new field of science
- ◆ **Solution to Darwin's Dilemma** -- discovery of the missing record, with new rules of Precambrian evolution: survival of the fittest *generalists*, descent *without* modification

READING: *Cradle of Life* -- Darwin's link to UCLA: Chpt. 4 (pp. 109-113); **Solution to Darwin's Dilemma:** Chpts. 1, 2 (pp.13-70)

OPTIONAL READING: *Cradle of Life* -- Oparin visits Dalí: Chpt. 4 (pp. 113-120); ***Evolution! Facts and Fallacies* -- overview of life's history:** Chpt. 1 (pp. 1-13)

Technical Terms

ecologic generalist _____ organism able to live in many different settings
ecologic specialist _____ organism adapted to a particular restricted setting
interbreed _____ mate and produce viable offspring
population _____ organisms of the same kind in a particular region
reproductive isolation _____ geographic or other isolation that prohibits mating

LECTURE 4 -- BEATING THE ODDS: HOW FOSSILS ARE PRESERVED

- ◆ **Fossils and extinctions subdivide Earth history** -- Precambrian vs. Phanerozoic; extinctions mark the ends of Phanerozoic eras
- ◆ **Types of preservation** -- impressions, compressions, petrifications, compactions, replacements, casts & molds, hard part preservation, miscellaneous
- ◆ **Common kinds of preservation** -- for plants: *petrifications*, impressions, compressions, casts & molds; ***plants have cell walls!*** for animals: *hard part preservation*, impressions, replacements; ***animals have hard parts!***

READING: See summary chart in Laboratory Manual!; *Cradle of Life* -- preservation problems: Chpt. 3 (pp. 71-75);

LAB 3: WHAT WAS THE EARLY ENVIRONMENT LIKE?

LECTURE 5 -- HOW DID LIFE GET STARTED?

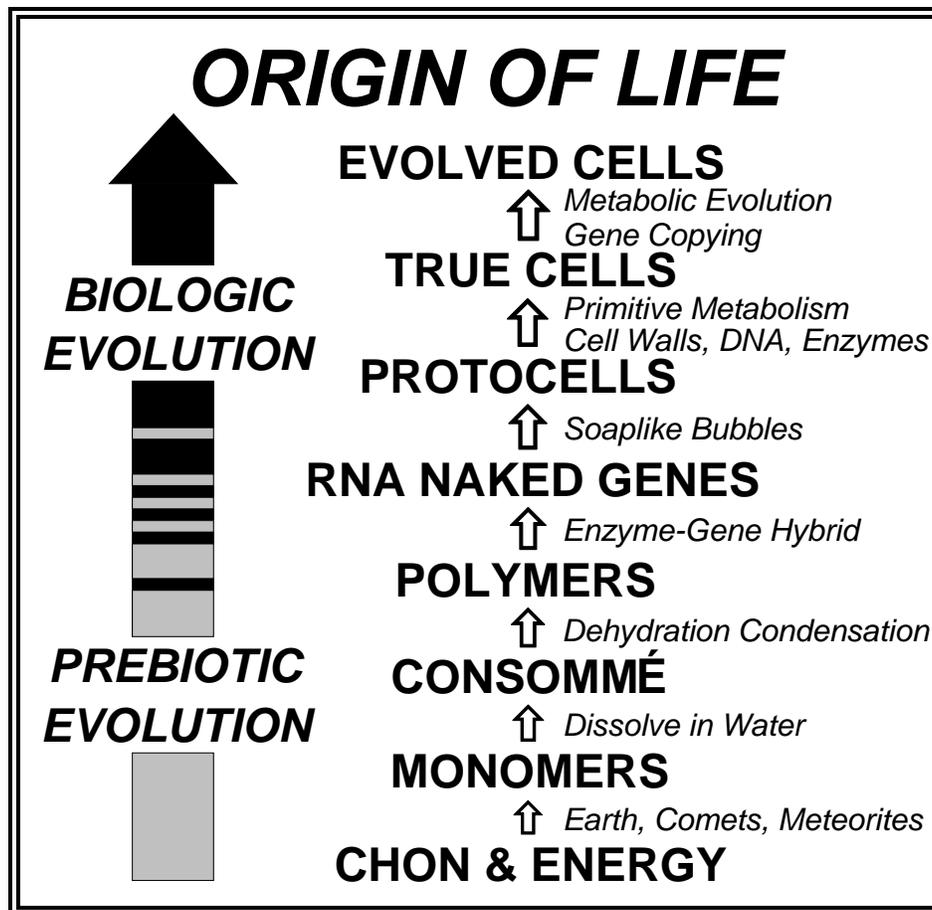
- ◆ **Scope vs. certainty of a scientific concept** -- the more all-encompassing and/or complex a concept is -- or the more distant it is in time or space from direct observation and/or experimental study -- the less likely it is to be completely certain: "facts" correlate with "pico-thinks" (one trillionth, 10^{-12} , of a "think"), "biogeopoetry" with "megathinks," concepts that are especially complex and remote such as the origin of life
- ◆ **Why is life in the solar system (evidently) limited to Earth?** -- What, if anything, is unique about the Earth? liquid water! Earth's surface 71% water, 29% land; Earth's solar system records: wettest spot, highest waterfall, longest river, largest lake, largest ocean (though Europa, moon of Jupiter, may have ice-covered ocean); overall, CHON + energy + liquid water \longrightarrow life; main steps in origin of life: CHON \longrightarrow organic monomers \longrightarrow organic polymers \longrightarrow cells
- ◆ **The chemistry of life is the chemistry of CHON** -- life is 99.9% carbon, hydrogen, oxygen, nitrogen (CHON).
- ◆ **Why CHON?** (1) four of the five most abundant elements in Universe; (2) link together in small sturdy compounds soluble in water (helium, the 5th most abundant, is inert, unable to bond to other elements)
- ◆ **"Organic" vs. "biologic"**-- "organic" is *not* the same as "living," *not* the same as "biologic": CHON-organics are made both by *nonbiologic* means (CHON + energy of starlight) and by biology -- the difference is how the organics are made, not what is made; CHON + starlight (energy) makes organics!
- ◆ **Organics beyond the Earth** -- CHON-organics (nonbiological) present in atmospheres of Jupiter, Saturn, Titan (Saturn's largest moon) and in comets, meteorites (e.g., Murchison carbon-rich meteorite), interplanetary dust particles; 85 kinds (many relevant to origin of life) detected by radioastronomy in enormous, interstellar clouds
- ◆ **A.I. Oparin: Our link to Darwin**-- Oparin visiting UCLA prof, 1976
- ◆ **CHON to monomers** -- Darwin's deduction: monomers "*might* be made"; Oparin's opinion: "*should* be made"; Miller's milestone: "*are* easy to make"; alternative ways to turn the trick (monomers made a deep-sea vents? monomers arrived on impacting meteorites, comets?)
- ◆ **Monomers to polymers** -- dehydration condensation; "chicken and egg" problem solved by ribozymes, gene-enzyme RNA hybrids of the RNA World
- ◆ **Polymers to cells** -- "like dissolves like"; water is like a magnet; from soap-like bubbles to cells

READING: Cradle of Life -- **CHON to polymers:** Chpt. 4 (pp. 108-113, 120-138); **polymers to cells:** Chpt 5 (pp. 139-143).

OPTIONAL READING: Major Events -- **monomer synthesis:** Chpt. 1 (pp. 1-28)

Technical Terms

- dehydration _____ removal of water, H-O-H
 condensation _____ linking of two molecules into one
 dehydration condensation _____ removal of H-O-H to link together two molecules
 ribozyme _____ RNA molecules having enzyme-like properties
 RNA World _____ hypothesized pre-DNA living world
 hydrophobic _____ "water-fearing," insoluble in water
 hydrophilic _____ "water-loving," soluble in water



LECTURE 6 -- ORIGINS OF THE GLOBAL ECOSYSTEM

- ◆ **The essentials of life** -- *necessities*: CHON and energy; *strategies*: heterotrophy (animal- like "feeders on others") and autotrophy (plantlike "self-feeders"); *two versions of each strategy*, primitive (anaerobic) and advanced (aerobic)
- ◆ **Metabolism evolved to satisfy the essentials of life** -- (1) earliest lifestyle: **anaerobic heterotrophy** (glycolysis) ; glycolysis reversed to yield glucose biosynthesis (gene copying, reversible enzymes). Anaerobic heterotrophy to (2) **anaerobic photoautotrophy** (non-oxygenic photosynthesis), freed life from need for abiotic organics. Anaerobic photoautotrophy to (3) **aerobic photoautotrophy** (O₂-producing photosynthesis), gave off oxygen gas toxic to competitors ("gas warfare"). Aerobic photoautotrophy to (4) **aerobic heterotrophy** (O₂-respiration, "breathing"), provided major increase in energy yield; has three parts: glycolysis (from anaerobic heterotrophs), citric acid cycle (from anaerobic photoautotrophs), electron carriers (from aerobic photoautotrophs); if O₂ absent, mammals revert to primitive metabolism (glycolysis, "fermentation").
- ◆ **How old is the modern ecosystem?** -- the "modern" ecosystem is ancient, not modern at all, invented by primitive microbes billions of years ago; dates from the first "**complete aerobes**"-- cyanobacteria, producers and consumers of O₂, evidenced by carbon isotopes, oxidized iron (in BIFs, banded iron formations), stromatolites, microfossils
- ◆ **Isotopic evidence of photosynthesis** -- stable carbon isotopes (¹²C, ¹³C) separated by CO₂-capturing enzyme; organics ¹²C-enriched, limestones ¹²C-depleted; firm signature to 3.5 Ga, possibly to 3.8 Ga
- ◆ **Geologic evidence of cyanobacterial (O₂-producing) photosynthesis** -- reactants: CO₂ (carbonate minerals of limestones) and H₂O (ripple marks, pillow lava); products: "CH₂O" (kerogen) and O₂ (oxidized iron minerals in BIFs)
- ◆ **Oxygen levels were slow to rise** -- oxygen buried in BIFs ("oxygen sinks"); unoxidized pyrite shows O₂ scarce to ~2 Ga

READING: *Cradle of Life* -- **metabolic evolution:** Chpt. 5 (pp. 150-163); **how old is the ecosystem?:** Chpt. 6 (pp. 164-166); **photosynthesis, isotopes:** Chpt. 6 (169-177).
OPTIONAL READING: *Major Events* -- **rise of oxygen:** Chpt. 2 (pp. 44-49)

Technical Terms

aerobic _____	pertaining to the presence of molecular oxygen
aerobic respiration _____	oxidation ("burning") of foodstuffs to yield energy
ammonia _____	hydrogenated nitrogen, NH ₃
anaerobic _____	pertaining to the absence of molecular oxygen
autotrophy _____	"self-feeding" lifestyle of plants and plantlike microbes
banded iron fm. _____	"BIF," a kind of sedimentary iron-rich rock
BIF _____	banded iron formation, a kind of sedimentary iron-rich rock
carbonate _____	CO ₃ -minerals or the rocks (e.g., limestones) they comprise

"CH₂O"	_____	abbreviation for glucose sugar, C ₆ H ₁₂ O ₆
citric acid cycle	_____	the cyclic part of the aerobic respiration pathway
complete aerobe	_____	organism capable of both producing and consuming O ₂
cyanobacteria	_____	early evolved O ₂ -producing/consuming bacterial prokaryotes
electron carriers	_____	compounds that convey electrons one to another
glucose	_____	the simple six-carbon sugar, C ₆ H ₁₂ O ₆
glucose synthesis	_____	metabolic conversion of pyruvate to glucose sugar
glycolysis	_____	anaerobic break-down of glucose sugar to pyruvate
heterotrophy	_____	"eating others" lifestyle of animals and animal-like microbes
microbe	_____	prokaryotic microorganism, either bacterial or archaeal
microfossil	_____	minute fossil, typically 100 μm or smaller
N₂-fixation	_____	metabolic conversion of atmospheric nitrogen to ammonia
oxidized iron	_____	iron +3, as in the iron oxide mineral hematite, Fe ⁺³ O ₃ ⁻²
oxygen sink	_____	substance (volcanic gases, reduced Fe) that sponges up O ₂
photoautotrophy	_____	autotrophy powered by light energy
photosynthesis	_____	photoautotrophy
pillow lava	_____	pillow-like masses formed when lava cools quickly in water
pyruvate	_____	salt of the simple 3-carbon compound pyruvic acid, C ₃ H ₄ O ₃
reduced iron	_____	iron +2, as in the iron sulfide mineral pyrite, Fe ⁺² S ₂ ⁻¹
stromatolites	_____	finely layered mound-like masses built by microbial communities

LAB 4: PRECAMBRIAN LIFE

LECTURE 7 -- THE OLDEST RECORDS OF LIFE

⇒⇒ **Top six questions about the oldest fossils known** (3,500 Ma-old microbes from Western Australia): (1) How do you know where to hunt? (2) What signs do you search for? (3) How do you know the fossils' age? (4) What kind of organisms are they and why do they matter? (5) What was the Earth like when the microbes were alive? (6) Will older fossils ever be found?

- ◆ **When was Earth ready for life?** -- No rocks have survived from Earth's earliest epoch; the Moon holds the answer!
- ◆ **When did life begin?** -- earlier than 3.5 Ga ago (oldest fossils), perhaps by 3.8 Ga ago (suggestive isotopic evidence), but later than 3.9 Ga ago (planet repeatedly sterilized by impacting meteorites, 4.5 to 3.9 Ga ago)

READING: *Cradle of Life* -- **oldest fossils:** Chpt. 3 (pp. 75-100); **so far, so fast, so early:** Chpt. 6 (pp. 166-169)

OPTIONAL READING: *Major Events* -- **early evolution:** Chpt. 2 (pp. 29-44)

LECTURE 8 -- EARTH'S OLDEST LIVING FOSSILS

- ◆ **Oldest evidence of life** -- biogenic carbon (last two lectures) and (this lecture) stromatolites, and cellular fossils
 - ◆ **What is a stromatolite?** -- layered microbial community; how stromatolites grow; comparison of modern and ancient stromatolites; stromatolites in Chinese architecture
 - ◆ **Three examples of Precambrian microbial communities** -- Bitter Springs Formation, 850 Ma-old, central Australia (cyanobacteria); Gunflint Formation, 2,100 Ma-old, southern Canada (cyanobacteria and extinct forms); Apex chert, 3,465 Ma-old, northwestern Australia ("cyanobacterium-like" filaments)
 - ◆ **Cyanobacteria: fossil-modern comparisons** -- "jelly beans" (Entophysalidaceae), "balls" (Chroococcaceae), "strings" (Oscillatoriaceae)
- ⇒⇒ **Modes and tempos in the evolution of life** -- G. G. Simpson and the rules of standard evolution; tempos of evolution: "fast" (tachytelic), "standard" (horotelic), "slow" (bradytelic), "super-slow" (hypobradytelic)
- ◆ **"The older the rock, the greater the chance it no longer exists!"** -- rocks/fossils less and less common in increasingly older terrains
 - ◆ **Cyanobacteria: evolution's most successful ecologic generalists** -- versatility reflects evolution of the world's environment; "Grand Champions" at warding off extinction

READING: *Cradle of Life* -- **stromatolites:** Chpt. 7 (pp. 183-208); **cyanobacteria:** Chpt. 8 (pp. 209-235)

OPTIONAL READING: *Major Events* -- **prokaryotic evolution:** Chpt. 2 (pp. 49-54)

Technical Terms

biogenic carbon	_____	carbon shown biologic in origin by its isotopic composition
bradytely	_____	slow evolution shown by Phanerozoic "living fossils"
Chroococcaceae	_____	taxonomic family of cyanobacteria ("balls")
Entophysalidaceae	_____	taxonomic family of cyanobacteria ("jelly beans")
hypobradytely	_____	extremely slow evolution shown by cyanobacteria
Oscillatoriaceae	_____	taxonomic family of cyanobacteria ("strings")

LECTURE 9 -- LIFE LIKE US HAS CELL LIKE OURS

- ◆ **The three domains of life** -- Bacteria, Archaea, Eucarya
- ◆ **Prepackaged evolution** --- endosymbiosis
- ◆ **The prokaryote-eukaryote difference** -- prokaryote = "before the nucleus," eukaryote = "truly nucleated"; prokaryote cells small (1 to 10 μm), have DNA and ribosomes, lack membrane-bounded organelles; eukaryote cells large (10 to 100 μm), contain nuclei, mitochondria and (in photosynthetic kinds) chloroplasts
- ◆ **How old are the eukaryotes?** -- nuclei almost never preserved; large-celled (>100 μm) eukaryotic phytoplanktonic microalgae ("acritarchs") date from 1,800 Ma ago
- ◆ **Eukaryotes perfect the art of cloning** -- simple (balloon-like, "sphaeromorph") acritarchs evolved slowly, 1,800 to 1,100 Ma ago, reproduced by mitosis ("cloning"); life's goal is to *not* to evolve!
- ◆ **Sex: a new lifestyle brings major change** -- sex = meiosis + fusion (syngamy) of sperm and egg (gametes); burst of acritarch kinds beginning 1,100 Ma ago (large cells, up to 1,000 μm = 1 cm; spiny acritarchs = "acanthomorphs"); gender determination in humans; *sex speeded evolution, promoted specialization, brought increased diversity*
- ◆ **Late Precambrian evolutionary** -- 1,100 Ma: *sexual reproduction* (rapid evolution, diversity, specialization); 950 Ma: *protozoans* and *seaweeds*; 570 Ma: *soft-bodied animals*, feeding burrows; 550 Ma: *shelly animals*, the "*Cambrian Explosion*"
- ◆ **Prelude to the Phanerozoic: many-celled animals enter the scene** -- enigmatic fossils of Ediacara, South Australia (very latest Precambrian = Vendian), oldest animals known
- ◆ **The Cambrian explosion** -- shelly fossils begin the Cambrian; mid-Cambrian (530 Ma-old) Burgess Shale fossils (discovered by C.D. Walcott, "Founder of Precambrian Paleobiology") show Cambrian explosion of new kinds of animals

READING: *Cradle of Life* -- **eukaryotes, mitosis, meiosis:** Chpt. 9 (pp. 236-259);

Ediacaran fauna: Chpt. 9 (pp. 259-263); **Cambrian explosion:** Chpt. 1 (pp. 23-29)

OPTIONAL READING: *Major Events* -- **early eukaryotes:** Chpt. 2 (pp. 54-61);

Ediacaran fauna: Chpt. 3 (pp. 65-89)

Technical Terms

acritarchs	_____	fossil eukaryotic phytoplankton, single-celled microalgae
chloroplast	_____	organelle for O ₂ -producing photosynthesis in eukaryotic cells
chromosome	_____	gene- (DNA-) containing elongate bodies in cell nuclei
diploid	_____	"2N," chromosome number in body cells, twice that in gametes
gamete	_____	egg or sperm
haploid	_____	"1N," chromosome number in gametes, 1/2 that in body cells
meiosis	_____	eukaryotic cell division that makes plant spores, animal gametes
mitochondrion	_____	organelle for aerobic respiration in eukaryotic cells
mitosis	_____	eukaryotic body cell division, makes exact copies ("clones")
syngamy	_____	fusion of gametes in sexual reproduction
X-chromosome	_____	gender-determining chromosome in humans (XX = female)
Y-chromosome	_____	gender-determining chromosome in humans (XY = male)

**MID-TERM
LAB EXAM**

**MID-TERM
LECTURE EXAM**

LAB 5: PLANTS CONQUER THE LAND

LECTURE 10 -- PLANTS CONQUER THE LAND

- ◆ **Plants truly matter!** -- global ecosystem: *no* eaters without eatees (plants), *no* air-breathers without O₂ (made by plants); use of plants: housing (wood), fuel (coal, petroleum), fibers (clothes, paper, rope), beauty (landscaping, bouquets), medicine (many plant-derived agents); plants protect from UV-light (give off O₂; O₂ + O (from H-O-H, water) makes O₃ [ozone]; ozone, O₃ shields UV-light); plants absorb CO₂ (in photosynthesis), decrease the CO₂-caused greenhouse effect
- ◆ **How plants work** -- complete aerobes: photosynthesize *and* breathe (produce and consume O₂); main parts (roots, stems, leaves, flowers); earliest had "naked" stems (no roots, no leaves)
- ◆ **Origin of land plants** - problems of evolving from water to land and how solved: root-like stem [**rhizome**] to absorb water; tubes to support height and move water [**xylem**] and move photosynthetically made sugar [**phloem**]; waxy skin [**epidermis**] to hold water in; pores [**stomates**] to absorb CO₂; waxy coating [**cutin**] to protect spores from drying; earliest fossil plant: *Cooksonia*
- ◆ **Spore plant life cycle** -- spores formed in spore sacs = sporangia (by meiosis); land on ground; grow (by mitosis); produce sperm and eggs (by mitosis); sperm swims to egg (*need water*); sperm and egg unite; fertilized egg grows to new spore-producing plant; life cycle repeats (only where water present for swimming sperm).
- ◆ **Spore plants rise to dominance** (Paleozoic) -- from naked stems to spiny stems to stems with microphylls (small, single-veined, true leaves), to stems with spiral microphylls: Rhyniophytes (*Rhynia*, *Cooksonia*), Lycophytes (*Asteroxylon*, and the "scale tree" *Lepidodendron*), Sphenophytes (*Calamites*)

READING: Read this week's lab exercise ("Plants") in Laboratory Manual!

OPTIONAL READING: Major Events -- early land plants: Chpt. 4 (pp. 95-116)

Technical Terms

- Cooksonia** _____ earliest known land plant (late Silurian, 410 Ma ago)
- cutin** _____ waxy coating on stems and spores, inhibits desiccation
- dicot** _____ kind of flowering plant have net-veined leaves; e.g., oak, maple
- epidermis** _____ outermost cell layer; plant "skin"
- monocot** _____ kind of flowering plant having parallel-veined leaves; e.g., grasses
- phloem** _____ thin-walled food-conducting tubes
- rhizome** _____ underground stem
- Rhynia** _____ early simple land plant (Devonian, 390 Ma ago)
- root** _____ anchoring organ, has cell structure different from stem
- sporangia** _____ sacs where spores are produced by meiosis
- spores** _____ haploid ("1N") products of meiosis in plants
- stomates** _____ pores in epidermis for absorption of carbon dioxide
- xylem** _____ strong, thick-walled, water-conducting tubes; "wood"

LECTURE 11 -- FROM SPORE PLANTS TO SEEDS AND FLOWERS

- ◆ **From spiny microphylls to large megaphylls** (complex fernlike leaves)
- ◆ **From fern-like spore plants to trees with naked seeds -- fossil seed ferns**, a so-called *missing link!*; seeds and wind pollination free plants from need for water for reproduction
- ◆ **Gymnosperms (plants with naked seeds) dominate the Mesozoic**; plants of Gondwanaland (*Glossopteris*) show modern landmasses were originally linked (South America-Falkland Islands-Antarctica-Africa-Madagascar-India)
- ◆ **Flowering plants (angiosperms) arise in mid-Cretaceous** (~100 Ma ago); co-evolution of insects and flowering plants; flowering plants (dicots and monocots) dominate the "modern" (Cenozoic) flora

READING: Read this week's lab exercise ("Plants") in Laboratory Manual!

LAB 6: ANIMALS WITHOUT BACKBONES

LECTURE 12 -- HOW PLANTS CHANGED THE PLANET: AN OVERVIEW

- ◆ **How plants evolved through time** -- *spore plants* invaded lowland marshes (late Silurian, ~410 Ma ago), but by their swimming sperm were tied to water for reproduction (Paleozoic: scale trees, horsetails, ferns); *naked-seed plants* (Mesozoic gymnosperms: seed ferns -- a so-called **missing link** having fern leaves but seeds, not spores -- cycads, *Ginkgo*, conifers); *flowering plants* having enclosed protected seeds (Cenozoic: dicots -- oak, maple; and monocots -- grass, palm)
- ◆ **Evolutionary advance #1: higher growth**, increased vegetative efficiency (in a competition for photosynthetic space, microphylls to megaphylls, twigs to shrubs to trees)
- ◆ **Evolutionary advance #2: improved reproduction** and better efficiency (spore plants tied to water for reproduction; pollinated seed plants invade the highlands; insect pollination in flowering plants improves reliability)
- ◆ **Plant evolution's great success #3: spread to new habitats** -- from marshy lowlands to arid uplands to the entire globe

READING: Read last week's lab exercise ("Plants") in Laboratory Manual!

LECTURE 13 -- "SEA SHELLS" AND THEIR KIN

- ◆ **Definitions** -- "animals" = Metazoa (invertebrates and backboneed vertebrates)
- ◆ **The Cambrian explosion** -- shelly fossils begin the Cambrian; mid-Cambrian (530 Ma-old) Burgess Shale fossils (discovered by C.D. Walcott, "Founder of Precambrian Paleobiology") show Cambrian explosion of new kinds of animals
- ◆ **The broadest groupings** -- bilaterians, protostomes and deuterostomes, acoelomates and coelomates; practically all date from Cambrian explosion
- ◆ **Earliest animal evolution** -- from sponges to molluscs
- ◆ **Relations among the many different kinds** -- shown by the rRNA Universal Tree of Life, embryos, larvae; adult tissues, body structure: protists to sponges to jellyfish and flatworms; then two paths, one to **insects** (the "protostome lineage": lampshells to molluscs (clams, snails, squids) to annelids -- via a **"missing link"** similar to members of the living tropical genus *Periptatus*, worms (like annelids) that unlike worms have jointed legs (like arthropods) -- to arthropods, including insects)

Technical Terms

- amniote egg** _____ hard-shelled egg of reptiles and birds
- bilateral** _____ two-fold symmetry
- blastopore** _____ pore in blastula that becomes either the anus or the mouth
- blastula** _____ ball of cells formed early in embryological development
- coelom** _____ body cavity between the body wall and the digestive tract
- deuterostome** _____ animals in which the blastopore becomes the adult anus
- ecothermy** _____ body heat absorbed from environment

ectoderm	_____	outermost cell layer
endoderm	_____	innermost cell layer
endothermy	_____	body heat generated by internal metabolism
lobe-finned fish	_____	fish with muscled fins, lineage leading to amphibians
lophophore	_____	arm-like feeding structure of brachiopods
mantle	_____	fleshy shell-secreting tissue of molluscs
mesoderm	_____	middle cell layer
notochord	_____	lengthwise flexible rod in vertebrate embryos
plycosaur	_____	primitive mammal-like reptiles
pentamerous	_____	five-fold symmetry
protostome	_____	animals in which the blastopore becomes the adult mouth
tetrapod	_____	four-legged vertebrate
therapsids	_____	advanced mammal-like reptiles
tube feet	_____	water-filled saclike "feet" of echinoderms
valve	_____	either of the paired shells of brachiopods and pelecypods

READING: Read this week's lab exercise ("Invertebrates") in Laboratory Manual!

LAB 7: BACKBONED ANIMALS LIKE US

LECTURE 14 -- THE LINEAGE LEADING TO HUMANS

- ◆ **Worms (via *Peripatus*) to jointed-legged arthropods**
- ◆ **Relations among the many different kinds** -- shown by the rRNA Universal Tree of Life, embryos, larvae; adult tissues, body structure: protists to sponges to jellyfish and flatworms; then two paths, one to *insects* (the "**protostome lineage**," last lecture), the other to *humans* (the "**deuterostome lineage**," from sea stars to vertebrates)
- ◆ **Echinoderms:** sea stars, sea urchins, crinoids, sand dollars

READING: Read last week's lab exercise ("Invertebrates") in Laboratory Manual!

LECTURE 15 -- BACKBONED ANIMALS TAKE OVER THE EARTH

- ◆ **Why is a chicken like a man?** (revisited) -- comparative anatomy of humans, other mammals, birds, reptiles, amphibians, and fish
- ◆ **Homologous vs. analogous traits** -- *homologous* organs and biochemical traits (same or similar function, share common evolutionary history -- e.g., bird wing and bat wing) vs. *analogous* organs and biochemical traits (share same or similar function but differ in evolutionary history -- e.g., bird wing and insect wing)
- ◆ **Evolution of backboned animals** -- from starfish to chordates, fish to amphibians, reptiles, birds and mammals; **amniote egg** enables vertebrates (viz., reptiles) to invade highlands
- ◆ **Mesozoic reptiles** highly successful, exceptionally varied (swimming, flying, creeping, crawling, lumbering, sprinting); birds = "flying feathered dinosaurs"
- ◆ **Thermoregulation:** Cold-blooded **ectotherms** evolve to warm-blooded **endotherms**
- ◆ **Mammals arise in Triassic** (~200 Ma ago), mammals **become dominant only at the end of the Mesozoic** (= end of the Cretaceous, ~65 Ma ago) when the extinction of dinosaurs opens new habitats to mammals

READING: Read this week's lab exercise ("Vertebrates") in Laboratory Manual!

OPTIONAL READING: Major Events -- vertebrate evolution: Chpt. 5 (pp. 119-139); human evolution: Chpt. 6 (pp. 141-172)

LECTURE 16 -- TAKE-HOME LESSONS ABOUT THE HISTORY OF LIFE

- ◆ **Evolution itself evolved!** -- Darwin's Dilemma: "missing" Precambrian fossil record; solution to Darwin's Dilemma: Precambrian Age of Microscopic Life; life's two great inventions, both Precambrian: oxygen-producing photosynthesis (cyanobacteria), eukaryotic sex (microalgae); sex caused evolution to evolve: from slow-changing Precambrian generalists (avoid extinction) to rapidly evolving Phanerozoic specialists (thrive then go extinct)

- ◆ **Nature is *not* compartmentalized** -- universities are compartmentalized but Nature is not -- as shown by the new interdisciplinary science of Precambrian paleobiology, to understand life and life's long history requires understanding of *biology/microbiology* (what are the different kinds of organisms?), *biochemistry/physiology* (how do organisms live?), *molecular biology* (how are the life forms related to one another?), *geology* (how long has life existed?), *organic chemistry* (how did life get started?), *astronomy/comparative planetology* (why did life take root on Earth?), *paleontology* (how did life change through time?), *evolutionary biology* (why did it change in the way it did?), *atmospheric science* (how has life affected the environment?)
- ◆ **The Ecosystem is simple** -- only two necessities (CHON, energy), two strategies (heterotrophy, strategy of animals and animal-like eaters; and autotrophy, strategy of plants and plantlike eaters); necessities/strategies explain life's history
- ◆ **Sequential co-evolution of plants and animals** -- eaters followed the eaters! -- in plants, spores (need water to reproduce) to naked seeds (wind pollinated, invade uplands) to flowers (enclosed seeds, insect pollinated) allowed plants to occupy the globe, followed in animals by amphibians (need water to reproduce) to reptiles (amniote egg, invade uplands) to mammals (protected fetus)
- ◆ **Intelligence has ancient roots** - Why aren't plants smart? (sessile autotrophs) Why aren't sponges or clams smart? (sessile heterotrophs) How do worms ferret out food? (mobile heterotrophic foragers) intelligence evolved from mobile heterotrophy, itself grounded in the need for CHON and energy that dates life's beginnings; from microbes to man, ignorance to intelligence, all life is linked!

READING: *Cradle of Life* -- lessons: Chpt. 10 (pp. 264-277)

LECTURE 17 -- HOW IS SCIENCE DONE?

- ◆ **The human side of science** -- unearthing a "Rosetta Stone" (the basalt tablet unearthed in 1799 that was key to deciphering Egyptian hieroglyphics); Feynman's First Principle: **"You must not fool yourself -- and you are the easiest person [for you] to fool!"**
- ◆ **"Man, Witness of the Deluge"** -- 1725, Johann Jacob Scheuchzer (1672-1733), Swiss physician, discovers *Homo diluvii testis*, "Man, a Witness of the Deluge"; for 100 years thought proof of Noah's Flood; 1811, Georges Cuvier (comparative anatomist, Founder of Paleontology) "cleans" the specimen, shows it to be a fossil giant salamander, not a proof of biblical truth
- ◆ **Beringer's "Lying Stones"** -- 1725, Johann Bartholomew Adam Beringer (1667-1740), professor and physician (Würtzburg, Germany) assembles amazing menagerie of "figured stones"; elated, prepares major treatise (*Lithographiae Wirceburgensis*) reporting the monumental find, only to discover he'd been hoaxed (by another professor and the university librarian) who despised his arrogance; like Scheuchzer's biblical "human," Beringer's "fossils" were Rosetta Stones that turned to dust

- ◆ **Ancient life on Mars?** -- 1996, NASA-staged press conference claiming evidence of past life on Mars; Carl Sagan's warning: "Extraordinary claims require extraordinary evidence!"; of the lines of evidence presented (minerals, organic compounds, and minute fossil-like objects), only the "fossils" -- if proven true -- could be a "smoking gun"; but in 1998 the "fossils" were shown to be mineralic artifacts, yet another Rosetta Stone turned to dust!
- ◆ **Lessons from the hunt** -- (1) scientists are human -- swayed by culture, accepted "truth," pull of a big breakthrough; (2) goal is to know, not just to guess -- "perhaps, possible, might be" are not firm answers and "feel-good" solutions do not count; (3) *most important*: science is self-correcting -- over time, firm facts always win out!

READING: *Cradle of Life* -- Scheuchzer, Beringer: Chpt. 11 (pp. 281-303);
hunt for life on Mars: Chpt. 12 (pp. 304-325)

OPTIONAL READING: *Evolution! Facts and Fallacies* -- science and the media:
Chpt. 4 (pp. 71-90); **extraterrestrial life:** Chpt. 6 (pp. 119-140).

**FINAL
LAB EXAM**

**FINAL
LECTURE EXAM**

Glossary of Technical Terms

acritarchs _____	fossil eukaryotic phytoplankton, single-celled microalgae
aerobic _____	pertaining to the presence of molecular oxygen
aerobic respiration _____	oxidation ("burning") of foodstuffs to yield energy
ammonia _____	hydrogenated nitrogen, NH ₃
amniote egg _____	hard-shelled egg of reptiles and birds
anaerobic _____	pertaining to the absence of molecular oxygen
Archaea _____	1 of 3 rRNA domains of life, composed of archaeal prokaryotes
autotrophy _____	"self-feeding" lifestyle of plants and plantlike microbes

Bacteria _____	1 of 3 rRNA domains of life, composed of bacterial prokaryotes
banded iron fm. _____	"BIF," a kind of sedimentary iron-rich rock
BIF _____	banded iron formation, a kind of sedimentary iron-rich rock
bilateral _____	two-fold symmetry
biogenic carbon _____	carbon shown biogenic in origin by its isotopic composition
blastopore _____	pore in blastula that becomes either the anus or the mouth
blastula _____	ball of cells formed early in embryological development
bradytely _____	slow evolution shown by Phanerozoic "living fossils"

carbonate _____	CO ₃ -minerals or the rocks (e.g., limestones) they comprise
Cenozoic Era _____	65 Ma ago to present (<i>Age of Mammals and Flowering Plants</i>)
chloroplast _____	organelle for O ₂ -producing photosynthesis in eukaryotic cells
"CH₂O" _____	abbreviation for glucose sugar, C ₆ H ₁₂ O ₆
CHON(SP) _____	carbon, hydrogen, oxygen, nitrogen (sulfur, phosphorus)
chromosome _____	gene- (DNA-) containing elongate bodies in cell nuclei
Chroococcaceae _____	taxonomic family of cyanobacteria ("balls")
citric acid cycle _____	the cyclic part of the aerobic respiration pathway
coelom _____	body cavity between the body wall and the digestive tract
complete aerobe _____	organism capable of both producing and consuming O ₂
condensation _____	linking of two molecules into one
Cooksonia _____	earliest known land plant (late Silurian, 410 Ma ago)
cutin _____	waxy coating on stems and spores, inhibits desiccation
cyanobacteria _____	early evolved O ₂ -producing/consuming bacterial prokaryotes

dehydration _____	removal of water, H-O-H
dehydration condensation _____	removal of water (H-O-H) to link together two molecules
deuterostome _____	animals in which the blastopore becomes the adult anus
dicot _____	kind of flowering plant have net-veined leaves; e.g., oak, maple
diploid _____	"2N," chromosome number in body cells, twice that in gametes
DNA _____	deoxyribonucleic acid, genetic material of cells
domain _____	superkingdom-like category of biologic systems

ecologic generalist	___	organism able to live in many different settings
ecologic specialist	___	organism adapted to a particular restricted setting
ecothermy	_____	body heat absorbed from environment
ectoderm	_____	outermost cell layer
electron carriers	_____	compounds that convey electrons one to another
endoderm	_____	innermost cell layer
endosymbiosis	_____	the living of one kind of organism within cells of another
endothermy	_____	body heat generated by internal metabolism
Entophysalidaceae	___	taxonomic family of cyanobacteria ("jelly beans")
enzyme	_____	biochemical that governs and speeds chemical reactions in cells
epidermis	_____	outermost cell layer; plant "skin"
Eucarya	_____	1 of 3 three rRNA domains of life, composed of eukaryotes
eukaryote	_____	organism (protist, plant, fungus, animal) having nucleated cells

Ga	_____	<i>giga anna</i> , one billion years (1×10^9 yr)
gamete	_____	egg or sperm
glucose	_____	the simple six-carbon sugar, $C_6H_{12}O_6$
glucose synthesis	_____	metabolic conversion of pyruvate to glucose sugar
glycolysis	_____	anaerobic break down of glucose sugar to pyruvate

haploid	_____	"1N," chromosome number in gametes, 1/2 that in body cells
heterotrophy	_____	"eating others" lifestyle of animals and animal-like microbes
horizontalist	_____	specialist on life and environment of a particular geologic time
hydrophilic	_____	"water-loving," soluble in water
hydrophobic	_____	"water-fearing," insoluble in water
hypobradytely	_____	extremely slow evolution shown by cyanobacteria

index fossil	_____	fossil distinctive of a particular segment of geologic time
interbreed	_____	mate and produce viable offspring

lobe-finned fish	_____	fish with muscled fins, lineage leading to amphibians
lophophore	_____	arm-like feeding structure of brachiopods

Ma	_____	<i>mega anna</i> , one million years (1×10^6 yr)
mantle	_____	fleshy shell-secreting tissue of molluscs
meiosis	_____	eukaryotic cell division that makes plant spores, animal gametes
mesoderm	_____	middle cell layer
Mesozoic Era	_____	250 to 65 Ma ago (<i>Age of Reptiles and Naked Seed Plants</i>)
metabolism	_____	the buildup or breakdown of biochemicals in cells
microbe	_____	prokaryotic microorganism, either bacterial or archaeal
microfossil	_____	minute fossil, typically 100 μ m or smaller
mitochondrion	_____	organelle for aerobic respiration in eukaryotic cells
mitosis	_____	eukaryotic body cell division, makes exact copies ("clones")
monocot	_____	kind of flowering plant having parallel-veined leaves; e.g., grasses

monomers _____ small "building block" compounds that link to make up polymers
mutation _____ change in the genetic material (DNA) of cells

N₂-fixation _____ metabolic conversion of atmospheric nitrogen to ammonia
notochord _____ lengthwise flexible rod in vertebrate embryos

Oscillatoriaceae _____ taxonomic family of cyanobacteria ("strings")
oxidized iron _____ iron +3, as in the iron oxide mineral hematite, Fe⁺³O₃⁻²
oxygen sink _____ substance (volcanic gases, reduced Fe) that sponges up O₂

Paleozoic Era _____ 550 Ma to 250 Ma ago (*Age of Animals Without Backbones and Spore Plants*)

pelycosaurs _____ primitive mammal-like reptiles

pentamerous _____ five-fold symmetry

Phanerozoic Eon _____ 550 Ma ago to present (*Age of Ecologically Specialized Megascopic Life*)

phloem _____ thin-walled food-conducting tubes

photoautotrophy _____ autotrophy powered by light energy

photosynthesis _____ photoautotrophy

pillow lava _____ pillow-like masses formed when lava cools quickly in water

polymers _____ large compounds composed of monomeric subunits

population _____ organisms of the same kind in a particular region

Precambrian Eon _____ formation of Earth (4,500 Ma ago) to 550 Ma ago (*Age of Ecologically Generalized Microscopic Life*)

prokaryote _____ organism (bacterium, archaean) having cells that lack a nucleus

protein _____ polymer made up of amino acids

protostome _____ animals in which the blastopore becomes the adult mouth

pyruvate _____ salt of the simple 3-carbon compound pyruvic acid, C₃H₄O₃

reduced iron _____ iron +2, as in the iron sulfide mineral pyrite, Fe⁺²S₂⁻¹

reproductive isolation _____ geographic or other isolation that prohibits mating

rhizome _____ underground stem

Rhynia _____ early simple land plant (Devonian, 390 Ma ago)

ribosomes _____ minute intracellular structures where proteins are made

ribozyme _____ RNA molecules having enzyme-like properties

RNA World _____ hypothesized pre-DNA living world

root _____ anchoring organ, has cell structure different from stem

rRNA _____ RNA (ribonucleic acid) present in protein-making ribosomes

sporangia _____ sacs where spores are produced by meiosis
spores _____ haploid ("1N") products of meiosis in plants
stomates _____ pores in epidermis for absorption of carbon dioxide
stromatolites _____ finely layered mound-like masses built by microbial communities
Superposition _____ "overlying"; in a sequence of (undeformed) sedimentary rocks,
"older below, younger above"
syngamy _____ fusion of gametes in sexual reproduction

tetrapod _____ four-legged vertebrate
therapsids _____ advanced mammal-like reptiles
tube feet _____ water-filled saclike "feet" of echinoderms

valve _____ either of the paired shells of brachiopods and pelecypods
verticalist _____ specialist on changes of life and environment over time

X-chromosome _____ gender-determining chromosome in humans (XX = female)
xylem _____ strong, thick-walled, water-conducting tubes; "wood"

Y-chromosome _____ gender-determining chromosome in humans (XY = male)
