OUTLINE:

(1) Geological Time Scale
(2) Origins of Life
(3) Oxygen Revolution
(4) Origin of Eukaryotes
(5) Origins of Multicellularity
(6) Cambrian Explosion
(7) Extinctions and Radiations

Geology plays an Important role in Evolutionary Thinking

Patterns of extinctions and evolutionary change in the fossil record were among the main influences on Darwin’s thinking

“There is grandeur in this view of life, with its several powers, having been originally breathed by the Creator into a few forms or into one; and that, whilst this planet has gone cycling on according to the fixed law of gravity, from so simple a beginning endless forms most beautiful and most wonderful have been and are being evolved.”

— Charles Darwin, The Origin of Species

Imagine...

That all of Earth History is compressed into a single year...

Life on Earth (4.6 billion years = 1 year)

- When did life first arise? And in what form?
- When did Eukaryotes arise?
- What about multicellular organisms (metazoans)?
- The invasion of land from the sea?
- Mammals?
- Humans?
The point of this exercise

- Life evolved under anaerobic conditions
- Much of the history of Life has been in the forms of prokaryotes and single cell eukaryotes (single cells)
- Multicellular organisms are relatively recent
- Humans have inhabited this planet for a very very short time

Key Events in Evolution of Life on Earth

- The first life on earth was in the form of prokaryotes
- The Oxygen Revolution was a pivotal event that transformed life on earth
- Humans have inhabited this planet for a very very short time

The 3 Domains of Life

- Phylogenetic relationships based on 18S rRNA sequences, showing clade separation of bacteria, archaea, and eukaryotes.
Animals
Colonization of land
Paleozoic
Meso-
zoic
Humans
Cenozoic
Origin of solar system and Earth

Prokaryotes
Proterozoic
Archaean
Billions of years ago

Multicellular eukaryotes
Single-celled eukaryotes
Atmospheric oxygen

Another way to look at the Geological Time Scale

Formation of Sedimentary rock

Fossils
(1) Hard parts mineralized (chemical reactions)
(2) Or the bone disintegrates mold filled with dissolved minerals
(3) Total preservation: amber, ice, bogs

Radiometric Dating
Can tell how old something is by how much radioisotope has disappeared

Each isotope has a known half-life, the time required for half the parent isotope to decay

Molecular Clock
Mutations
On average, mutations occur at a given rate

Example:
Mitochondria: ~2.2%/million years.

Faster if
Mutation rate is faster if:
- Shorter generation time (more meiosis or mitosis per time)
- Sloppy polymerase (e.g. HIV)
- Inefficient mismatch repair, etc.
Is the fossil record roughly congruent with timing of events based on the molecular clock?

Roughly so, but gaps in the fossil record

And molecular clock varies among genes and species

- Cenozoic
- Mesozoic
- Paleozoic
- Precambrian

- Origin of solar system and Earth
- Origin of mammals (165 mya)
- Cretaceous mass extinction (65 mya)
- Cambrian explosion (550–530 mya)
- Multicellular eukaryotes
- Single-celled eukaryotes

570 mya: Cambrian Explosion
65 mya: Cretaceous Extinction (dinosaurs go extinct)
230 mya: Permian Extinction
Boundaries between Eras

Marked by Explosive Adaptive Radiations And Mass Extinctions

Mass Extinction Events

Adaptive Radiations
Divergence of a phylogenetic group into forms adapted to various ecological niches.

- Happens over short geological time (~5 million years)
- Change in environment (Global Climate Change)
- Open Niches due to Extinction
  Or exploitation of new Niche (due to novel trait)
- Examples: Response to climate change, Colonization of Land, Air (flight), Cold, High Altitude, colonization of islands

Adaptive radiation often results in a star phylogeny

Star phylogeny

Rapid speciation: Can’t tell which taxa diverged first

65 mya: Cretaceous Extinction (dinosaurs go extinct)

230 mya: Permian Extinction

570 mya: Cambrian Explosion
**Cenozoic**: Age of Mammals

**Mesozoic**: Age of Reptiles

**Paleozoic**: Age of Invertebrates

**Precambrian**: Age of Single Cell

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**ERA: Precambrian**

"Age of the Single Cell"

90% Earth History

- Origin of Life
- Prokaryotes
- Oxygen
- Eukaryotes
- First animals

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The Earth was formed ~4.6 billion years ago.

Earth's early atmosphere likely contained water vapor and chemicals released by volcanic eruptions (nitrogen, nitrogen oxides, carbon dioxide, methane, ammonia, hydrogen, hydrogen sulfide) → chemically reducing.

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Life on Earth has a specific chemistry

- What were the earliest life forms?

- Prokaryotes are the earliest life forms we know of, but what might have preceded them?

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- Very specific Chemical Chirality and stereochemistry: L-Amino Acids, cis-fats, and D-sugars
  - Thought to result from the chiral spin or our galaxy and magnetic orientation

- DNA and RNA are also chiral due to their sugar backbone

- Chirality is important in foods:
  http://www.uoguelph.ca/news/2013/11/right_or_left_hands_matter_fats_foods_drugs_computers_guelph_study.html
• Mirror image life would kill us all:

Protobionts

• Replication and metabolism are key properties of life
• Experiments demonstrate that protobionts could have formed spontaneously from abiotically produced organic compounds
• For example, small membrane-bounded droplets called liposomes can form when lipids or other organic molecules are added to water

RNA World

• RNA can both serve as the genetic code (hereditary material) and also perform enzymatic functions (ribozymes)
• RNA molecules called ribozymes have been found to catalyze many different reactions
  – For example, ribozymes can make complementary copies of short stretches of their own sequence or other short pieces of RNA
  – Natural selection in the laboratory has produced ribozymes capable of self-replication (Herron& Freeman written prior to this discovery) http://www.ncr.org/chemistryworld/News/2007January/02011501.asp

Self-Replicating RNA and the Dawn of Natural Selection

• The early genetic material might have formed an “RNA world”
• The first genetic material was probably RNA, not DNA
• Early life forms might have consisted of protobionts with RNA as the genetic code
• Early protobionts with self-replicating, catalytic RNA would have been more effective at using resources and would have increased in number through natural selection

Self-Replicating RNA and the Dawn of Natural Selection

Ribozymes (= RNA enzyme or catalytic RNA)

RNA that can catalyze chemical reactions. Many natural ribozymes catalyze either the breaking or synthesis of phosphoester bonds in DNA or RNA. Such capacity would enable the capacity to self replicate and propagate life.

The functional part of the ribosome, the molecular machine that translates RNA into proteins, is fundamentally a ribozyme
RNA World

- RNA can both serve as the genetic code and also perform enzymatic functions (ribozymes)

- But, can RNA self-replicate? If so, it would have all components to be considered “life”

- Laboratory experiments indicate that RNA can self-replicate

These are all hypotheses, subject to testing

We do not actually know what the earliest forms of life were like... The RNA world and any other scenario is a hypothesis

What scientists are doing is testing what is chemically, physically, and biologically possible, given the conditions of the early Earth
ERA: Precambrian
“Age of the Single Cell”

90% Earth History
Origin of Life
Prokaryotes
Oxygen
Eukaryotes
First animals

Stromatolites

The oldest known fossils are of cyanobacteria from Archaean rocks of western Australia, dated 3.5 billion years old

Oxygen Revolution

By about 2.7 billion years ago, \( O_2 \) began accumulating in the atmosphere and rusting iron-rich terrestrial rocks

- “Oxygen revolution” from 2.7 to 2.2 billion yrs ago
  - \( O_2 \) in the atmosphere was generated by photosynthetic activity of cyanobacteria
  - Posed a challenge for life (\( O_2 \) toxicity)
  - Provided opportunity to gain energy from light
  - Allowed organisms to exploit new ecosystems

- \( \text{Photosynthesis: } 6 \text{ CO}_2 + 6 \text{ H}_2\text{O} + \text{photons} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6 \text{ O}_2 \)
Oxygen Revolution

- O₂ allows the production of more energy and more efficient metabolism
  \[ \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \rightarrow 6\text{CO}_2 + 6\text{H}_2\text{O}, \Delta G = -2880 \text{kJ per mole of C}_6\text{H}_{12}\text{O}_6 \]
  - Aerobic metabolism: 36 ATP molecules per glucose
  - Anaerobic metabolism: 2 ATP molecules per glucose
  - Aerobic and anaerobic metabolism share the initial pathway of glycolysis but aerobic metabolism continues with the Krebs cycle and oxidative phosphorylation.

- However, Oxygen is also Toxic
  - Oxygen is highly toxic to many species
  - Electrons that escape from the electron transport chain can bind to oxygen and produce reactive oxygen species
  - Reactive oxygen species (H₂O₂, O₂⁻) can damage DNA and other molecules

Evolutionary History dictates type of Metabolism

- The fact that much of prokaryotic life evolved BEFORE the oxygen revolution is reflected in the diverse forms of anaerobic metabolism
  - Most bacteria do not require oxygen, and for many it is toxic
  - Most bacteria use other molecules as the terminal electron acceptor when making ATP

- The fact eukaryotic life evolved AFTER the oxygen revolution is reflected in the fact that all eukaryotes use aerobic metabolism
  - They use oxygen as the terminal electron acceptor in energy production

Incredible Metabolic Diversity

- Some prokaryotes can use inorganic chemicals as the electron donor in the redox reaction of making ATP (respiration)
  (animals use organic carbon, food, as the electron donor)

- Eukaryotes can use only oxygen as the terminal electron acceptor when making ATP in the electron transport chain (aerobic respiration)

- Prokaryotes can use NO₃⁻, NO₂⁻, SO₄²⁻, etc. (anaerobic respiration)

- Some are photosynthetic

- Some can fix nitrogen, converting atmospheric N₂ → NH₃

The First Eukaryotes

The hypothesis of endosymbiosis proposes that mitochondria and plastids (chloroplasts and related organelles) were formerly small prokaryotes living within larger host cells (talk about this in Next Lecture)

- An endosymbiont is a cell that lives within a host cell

Endosymbiotic Theory

- Certain organelles originated as free-living bacteria that were taken inside another cell as endosymbionts.
- Mitochondria developed from proteobacteria (in particular, Rickettsiales or close relatives) and plastids from cyanobacteria
- Both mitochondria and plastids contain DNA that is different from that of the cell nucleus and that is similar to that of bacteria (in being circular in shape, its size, and DNA composition)

ERA: Precambrian

“Age of the Single Cell”

90% Earth History
Origin of Life
Prokaryotes
Oxygen
Eukaryotes
First animals
The organelles (mitochondria and chloroplasts) greatly aid in energy production in eukaryotes.

Given the evolutionary history of endosymbiosis (or endosymbiogenesis) leading to eukaryotes, eukaryotes will inevitably share traits with both archaea and bacteria.

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<td>Cambrian</td>
<td>500Mya - 545Mya</td>
<td>Multicellular</td>
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What is an Animal?

Multicellular (metazoan)
Heterotrophic (eat, not photo or chemosynthetic)
Eukaryote

No Cell Walls, have collagen
Nervous tissue, muscle tissue

Particular Life History-developmental patterns (Next lecture)
Origins of Multicellularity

It is thought that metazoans arose from Colonial flagellate protists

Oxygen Revolution:
- allow higher metabolic rate
- larger body size
- powered motion

But this hypothesis is also controversial

(1) Precambrian-Paleozoic Boundary (~570 MYA)
Fossil Deposits: Doushantu fossils Ediacaran fossils Burgess Shale

Cambrian Explosion

Cambrian Explosion (~570 MYA, in the geological record)

Radiations:
- Evolution of hard body parts
- Diversification of body forms
- Radiation of Invertebrates

Extinctions????
- Hard to tell, Precambrian species were single cell, soft
The Cambrian Explosion

- The Cambrian explosion originally referred to the sudden appearance of fossils resembling modern phyla in the Cambrian period (~543 to 525 million years ago)—mostly based on the Burgess Shale fossils.

- Phylogenetic analysis suggest that many animal phyla diverged before the Cambrian explosion recorded in the fossil record, perhaps as early as 700 million to 1 billion years ago.

Are Genetic Distances and fossil record roughly congruent?

Is the fossil record roughly congruent with timing of events based on the molecular clock?

Roughly so, but gaps in the fossil record.

And molecular clock varies among genes and species.

Was the Cambrian Explosion an Explosion?

Geology: YES
Sudden Appearance of Animal Fossils

Genetics: NO
DNA Divergences Predate Cambrian

Based on phylogeny of animals based on DNA sequence data, the radiation of animals predates the geological record of the Cambrian Explosion.
Fossil Record vs Molecular Clock

- Molecular clock and fossil record are not always congruent
  - Fossil record is incomplete, and soft bodied species are usually not preserved
  - Mutation rates can vary among species (depending on generation time, replication error, mismatch repair)
- But they provide complementary information
  - Fossil record contains extinct species, while molecular data is based on extant taxa
  - Major events in fossil record could be used to calibrate the molecular clock

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The Cambrian Explosion: Major Fossil Formations

- **Doushantuo Formation (Southern China):** 570 million years ago
- **Ediacaran Fauna (Australia):** 565-544 million years ago
- **The Burgess Shale (British Columbia, Canada):** 525-515 million yrs ago

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Doushantuo formation Southern China

- 570 million years ago
- Clusters of cells (embryos?)
- Sponges

Fossilized metazoan embryo at the 256 cell stage

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The Cambrian Explosion

- The Doushantuo fossils in China provide evidence of modern animal phyla tens of millions of years before the Cambrian explosion recorded in the Burgess Shale (~570 million years ago)

The Chinese fossils, along with DNA data, suggest that the Cambrian explosion occurred over a more extended period of time than previously thought
Ediacaran Fauna

- 565-544 million years ago
- Soft-body animals, sponges, jellyfish, ctenophores
- No evidence of locomotion

Burgess Shale Fauna

- Marrella
- Hallucigena
- Canadia

The Paleozoic Sea

Burgess Shale
http://www.burgess-shale.bc.ca/
Burgess Shale Fauna

- British Columbia, Canada
- 525-515 million yrs ago
- All animal phylum found

Marrella
Most common Fossil in the Burgess Shale

Why?

Ecological arms race?
Increase in oxygen?
(higher energy, larger animals possible)

Evolution of Animal Body Plans

- True Tissues
- Tissue Layers (Diplo vs Triploblasts)
- Body Symmetry
- Evolution of body cavity (Coelom)
- Evolution of Development

Cambrian Explosion
But major body plans evolved within a short period of time.

Of course, evolution continued after the Cambrian Explosion.

How could this happen? (genetic mechanism?) Later LECTURE:

Cambrian Explosion → Origins of Animals: I will discuss the genetic mechanisms of this Adaptive Radiation in the lecture on Animal Diversity.

Gene Regulatory Networks and the Evolution of Animal Body Plans

Brett H. Davidson and Douglas H. Erwin

Development of the animal body plan is controlled by large gene regulatory networks (GRNs), and hence evolution of body plans must depend upon change in the architecture of developmental GRNs. However, these networks are composed of diverse components that evolve at different rates and in different ways. Because of the hierarchical organization of developmental GRNs, some kinds of change affect internal properties of the body plan such as occur in speciation, whereas others affect major aspects of body plan morphology. A notable feature of the paleontological record of animal evolution is the establishment by the Early Cambrian of virtually all physiology-level body plans. We identify a class of GRN component, the "tweaks" of the network, which, because of their developmental role and their particular internal structure, are most sensitive to change. Conservation of phylogenetic body plans may have been due to the retention since pre-Cambrian time of GRN tweaks, which underlie development of major body parts.


ERA: Paleozoic

"Age of Invertebrates"
The Colonization of Land

- **Precambrian**: colonization of land by bacteria
- **Late Ordovician–Late Devonian**: Terrestrial ecosystems of plants, fungi, arthropods and eventually vertebrates
- **Late Silurian**: vascular plants
- **Devonian**: evidence of interactions among groups (fungal-plant symbiosis, arthropod herbivory)
- **Late Devonian**: Two major megadclades that were major participants in the Cambrian explosion appear on land
  - The lophotrochozoans: gastropod and bivalve mollusks, oligochaete annelids, rotifers, etc.
  - The ecdysozoans: arthropods, nematodes, etc.
- **Radiations**: Reptiles (dinosaurs)
- **Extinctions**: ~96% of species (esp. marine) All trilobites

The invasion of land by crustaceans (terrestrial crustaceans = insects)

- **PermianExtinction**
  - Radiations: Reptiles (dinosaurs)
  - Mammals, Birds (which are dinosaurs) appear
  - Extinctions: ~96% of species (esp. marine) All trilobites
Mesozoic-Cenozoic (KT) Boundary (65 MYA)

Cretaceous Extinction (KT Boundary, 65 million years ago)
- Caused by asteroid impact, with dust, ash, soot blocking sun, causing rapid global cooling
- 60-80% of species living at the time went extinct: dinosaurs (except for birds), pterosaurs, marine reptiles
- Mammals, crocodilians, amphibians, turtles unharmed

End of Mesozoic

Radiations:
- Mammals, Birds
- Flowering plants appear pollinating insects

Extinctions:
- End of Dinosaurs (except for birds)
- < 50% Marine species
Boundaries between Eras

Marked by Explosive Adaptive Radiations And Mass Extinctions

Adaptive Radiations

Divergence of a phylogenetic group into forms adapted to various ecological niches.

- Happens over short geological time (~5 million years)
- Change in environment (Global Climate Change)
- Open Niches due to Extinction
  Or exploitation of new Niche (due to novel trait)
- Examples: Response to climate change, Colonization of Land, Air (flight), Cold, High Altitude, colonization of islands

Adaptive Radiations

On the islands of Hawaii

Adaptive radiation often results in a star phylogeny

Rapid speciation: Can’t tell which taxa diverged first
**Total extinction rate (families per million years):**

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**Causes of Extinctions?**

- **Environmental change**
- **Global Warming or Cooling**

**Examples:**

- Permian Extinction: global warming
- Cretaceous Extinction: global cooling

**The “Big Five” Extinctions**

- **End Ordovician (~ 440 mya)**
- **Late Devonian (~365 mya)**
- **End Permian (~ 250 mya)**
- **End Triassic (~215 mya)**
- **End Cretaceous (~ 65 MYA)**

Did extinctions also accompany the Cambrian Explosion? Don’t know, prior species were soft and did not preserve.

**The ‘Big Five’ mass extinction events**

- **The Ordovician event** ended ~450 Myr ago; within 3.3 to 1.9 Myr 57% of genera were lost, an estimated 86% of species. Onset of alternating glacial and interglacial episodes; repeated marine transgressions and regressions. Uplift and weathering of the Appalachians affecting atmospheric and ocean chemistry. Sequestration of CO$_2$.

- **The Devonian event** ended ~359 Myr ago; within 29 to 2 Myr 35% of genera were lost, an estimated 75% of species. Global cooling (followed by global warming), possibly tied to the diversification of land plants, with associated weathering, pedogenesis, and the drawdown of global CO$_2$. Evidence for widespread deep-water anoxia and the spread of anoxic waters by transgressions.

- **The Permian event** ended ~251 Myr ago; within 2.8 Myr to 160 Kyr 56% of genera were lost, an estimated 96% of species. Siberian volcanism. Global warming. Spread of deep marine anoxic waters. Elevated H$_2$S and CO$_2$ concentrations in both marine and terrestrial realms. Ocean acidification.

- **The Triassic event** ended ~200 Myr ago; within 8.3 Myr to 600 Kyr 47% of genera were lost, an estimated 80% of species. Activity in the Central Atlantic Magmatic Province (CAMP) thought to have elevated atmospheric CO$_2$ levels, which increased global temperatures and led to a calcification crisis in the world oceans.

- **The Cretaceous event** ended ~65 Myr ago; within 2.5 Myr to less than a year 40% of genera were lost, an estimated 76% of species. A bolide impact in the Yucatán is thought to have led to a global cataclysm and caused rapid cooling. Preceding the impact, biota may have been declining owing to a variety of causes: Deccan volcanism contemporaneous with global warming; tectonic uplift altering biogeography and accelerating erosion, potentially contributing to ocean eutrophication and anoxia episodes. CO$_2$ spike just before extinction, drop during extinction.
Background vs Mass Extinction

- **Mass Extinctions**: Only 4%
  - Mass Extinctions kill off a very large % of the species on the planet at a given time, but because they are short in duration, they comprise a small % of animals that ever lived on the planet

- **Background Extinctions**: 96%
  - Extinctions are always happening in the background, and over a long long period of time, these extinctions add up to a lot of species extinctions

- 99% of species that have lived are extinct

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6th Mass Extinction

- Current extinctions:
  - http://www.actionbioscience.org/newfrontiers/eldredge2.html
  - http://www.nature.com/nature/journal/v471/n7336/full/nature09678.html
  - Overly successful fitness of human populations (outcompeting all other species)
    - Habitats destruction (agriculture, construction, etc)
    - Invasive species
    - Spreading of pathogens
    - Killing species directly
    - Global Climate Change

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Human Population Explosion

- The advent of Agriculture ~10,000 yrs ago led to human population explosion

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Global Warming

- Northern Hemisphere Temperature AD 1900-1999
6th Mass Extinction?

So, is a Mass Extinction currently underway?

If so, how does it compare to previous Mass Extinctions?

Assessing Mass Extinction

To document where the current extinction episode lies on the mass extinction scale requires us to know both:

(1) Whether current extinction rates are above background rates (and if so, how far above)

(2) How closely historic and projected biodiversity losses approach 75% of the Earth’s species.

Assessing Mass Extinction

Rates and magnitude of current species extinctions are compared to background extinction rates estimated from the fossil record

Problems:

- Many existing clades are undersampled or unevenly sampled (for many groups, we don’t know the current level of biodiversity)
- Species for which we have fossil data (marine gastropods, etc) tend to differ from those for which we have best modern data (terrestrial animals)

Data on the Current Mass Extinction

Studies estimated current rates of extinction to be orders of magnitude higher than the background rate

- Barnosky et al. 2011
  http://www.nature.com/nature/journal/v471/n7336/full/nature09678.html
- Ceballos et al. 2015
  http://advances.sciencemag.org/content/1/5/e1400253

Estimating rate and magnitude of current extinctions

- **Rate**: number of extinctions divided by the time over which the extinctions occurred. One can also derive from this a proportional rate—the fraction of species that have gone extinct per unit time.
- **Magnitude**: percentage of species that have gone extinct.
- **Mass Extinction**: when extinction rates accelerate relative to origination rates such that over 75% of species disappear within a geologically short interval—as short as ~2 million years, in some cases much less.

REVIEW

http://www.nature.com/nature/journal/v471/n7336/full/nature09678.html

Has the Earth’s sixth mass extinction already arrived?

On the horizon is expected to be a sixth mass extinction event in which over 90% of marine species are estimated to be lost, followed by the loss of over 75% of terrestrial species in a very short period of time. This rate is 10,000 times higher than the extinction rate during the Cretaceous event and 200 times higher than the rate of extinction during the Permian event. The current extinction rate has been estimated to be at least 100 times higher than the rate of extinction during the Cretaceous event, and possibly as high as 1,000 times higher. The current extinction rate is also estimated to be higher than the rate of extinction during the Permian event, and possibly as high as 20 times higher.

The current extinction rate has been estimated to be at least 100 times higher than the rate of extinction during the Cretaceous event, and possibly as high as 1,000 times higher. The current extinction rate is also estimated to be higher than the rate of extinction during the Permian event, and possibly as high as 20 times higher.
The current extinction has just started. So, how many more years it would take for current extinction rates to produce species losses equivalent to Big Five magnitudes?

- If all ‘threatened’ species became extinct within a century, and that rate then continued unabated, terrestrial amphibians, bird, and mammal extinction would reach Big Five magnitudes in ~240 to 540 years (241 ± 7 years for amphibians, 536.6 ± 9 years for birds, 334 ± 4 years for mammals).
- If extinction were limited to ‘critically endangered’ species over the next century and those extinction rates continued, the time until 70% of species were lost per group would be 890 years for amphibians, 2,265 years for birds and 1,515 years for mammals.
- For scenarios that project extinction of ‘threatened’ or ‘critically endangered’ species over 500 years instead of a century, mass extinction magnitudes would be reached in about 1,200 to 2,660 years for the ‘threatened’ scenario (1,209 ± 10 years for amphibians, 2,683 ± 7 years for birds and 1,672 years for mammals) or ~4,450 to 11,330 years for the ‘critically endangered’ scenario (4,452 ± 21 years for amphibians, 11,326 ± 4 years for birds and 7,550 ± 6 years for mammals).

This emphasizes that current extinction rates are higher than those that caused Big Five extinctions in geological time; they could be severe enough to carry extinction magnitudes to the Big Five benchmark in as little as three centuries.

**Approach**

Ceballos et al. 2015

http://advances.sciencemag.org/content/1/5/e1400253

- First, use a recent estimate of a background rate of 2 mammal extinctions per 10,000 species per 100 years (that is, 2 E/MSY), which is twice as high as widely used previous estimates.
- Then compare this rate with the current rate of mammal and vertebrate extinctions.

**Results**

Ceballos et al. 2015

http://advances.sciencemag.org/content/1/5/e1400253

- Sixth mass extinction is already under way
- Average rate of vertebrate species loss over the last century is up to 100 times higher than the background rate.
- Under the 2 E/MSY background rate, the number of species that have gone extinct in the last century would have taken, depending on the vertebrate taxon, between 800 and 10,000 years to disappear.
**Cumulative Vertebrate Extinctions**

Ceballos et al. 2015

Fig. 1 Cumulative vertebrate species recorded as extinct or extinct in the wild by the IUCN (2012). Graphs show the percentage of the number of species evaluated among mammals (5513; 100% of those described), birds (10,425; 100%), reptiles (4414; 44%), amphibians (6414; 88%), fishes (12,457; 38%), and all vertebrates combined (39,223; 59%). Dashed black curve represents the number of extinctions expected under a constant standard background rate of 2 E/MSY. (A) Highly conservative estimate. (B) Conservative estimate.

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**If extinctions of the last 114 yrs occurred under the background rate**

Ceballos et al. 2015

Fig. 2 Number of years that would have been required for observed vertebrate species extinctions in the last 114 years to occur under a background rate of 2 E/MSY. Red markers, highly conservative scenario; blue markers, conservative scenario. Note that for all vertebrates, observed extinctions would have taken between 800-10,000 years to disappear, assuming 2 E/MSY. Different classes of vertebrates show similar trends.

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**Past vs Modern Extinctions**

- **Past extinctions:**
  - Over millions of years (though KT meteor impact was quick)
  - Lead to adaptation radiation of new species
- **Current extinctions:**
  - Over decades/centuries (much faster than the Big Five)
  - No radiation of larger-bodied species
  - Habitat is occupied by humans rather than by new species
  - Species recover and radiate when the extinction dissipates: currently no end of extinction in sight
- Article by Paleontologist Niles Eldredge
  - [http://www.actionbioscience.org/newfrontiers/eldredge2.html](http://www.actionbioscience.org/newfrontiers/eldredge2.html)

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**Modern Extinction**

- Adaptive Radiations of:
  - Disease organisms (HIV, Ebola, Zika, West Nile, Sars)
  - Human commensals (lice)
  - Invasive Species (adapted to unstable environments)
  - Genetically-Modified Organisms?

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**Synthetic Life**

- Humans can now create synthetic life, by constructing a genome on the computer, synthesizing the DNA and injecting the genetic code into a cell
  - [http://www.sciencemag.org/content/328/5981/958.summary](http://www.sciencemag.org/content/328/5981/958.summary)
Summary

(1) Geological Time Scale
(2) Major Episodes in the History of Life
(3) Extinctions and Radiations

Concepts

Geological Time Scale
Four Eras
Origins of Life
Oxygen Revolution
Molecular Clock
Cambrian “Explosion”
Extinction
Adaptive Radiation
Mass Extinctions
Sixth Mass Extinction

Questions

• What are some of the key biological revolutions that occurred during the history of life on earth, and how did they come about?
• Why is it hypothesized that early life on earth was in the form of RNA?
• How did the Oxygen Revolution come about?
• What are the implications of a high oxygen atmosphere for organismal physiology?
• How were Eukaryotes created?
• What are animals?
• About when did animals evolve? Is there congruence between fossil estimates versus molecular clock estimates of the timing?
• How did animals diversify (“Cambrian Explosion”)? What are the genetic mechanisms?
• What are Extinctions and Radiations?
• What is the 6th Mass Extinction, and how does it differ from previous Extinctions?

Study Question:

Put the following Key Events in order:

(1) The Appearance of Dinosaurs
(2) The Oxygenation of the Atmosphere
(3) The Appearance of Bacteria
(4) The Appearance of Plants
(5) The Invasion of Land from the Sea
(6) The Appearance of Eukaryotes

(you don’t need to memorize the nitty gritty details on the history of life, but I want you to develop a general sense of time scale of the major events in evolutionary history- in Table 25.1 and in this lecture)

1. You are a geologist, and while digging through a rock formation, you have come across a layer of fossils characterized by animals with lots of hard parts, segments, and diverse body shapes. There are a lot of trilobites, and also some very strange-looking animals (alien-like, with multiple eyes, spines, claws, jaws, etc.). As you keep on digging below this layer, what are you likely to find?

   (A) Not much, some tiny round objects
   (B) Lots of plant species
   (C) Dinosaurs, birds, early mammals
   (D) More and more complex and specialized species

2. Choose the correct sequence of events in the History of Life.

   (A) Origin of Life, oxygen in atmosphere, bacteria, eukarya, origin of animals, dinosaurs, mammals.
   (B) Origin of Life, oxygen in atmosphere, eukarya, origin of invertebrates, origin of vertebrates, dinosaurs, mammals
   (C) Origin of Life, eukarya, oxygen in atmosphere, origin of invertebrates, origin of vertebrates, dinosaurs, mammals
   (D) Origin of Life, oxygen in atmosphere, eukarya, origin of vertebrates, dinosaurs, Cambrian Explosion, mammals
3. Which of the following is FALSE regarding extinctions and radiations?
(A) The major eras in the geological time scale is marked by extinctions and radiations
(B) Extinctions are of a major concern today because species extinctions are not being accompanied by major radiations, as the habitats where extinctions have occurred have been removed or are occupied by humans
(C) Genetic drift and inbreeding can increase the chances that a population will go extinct
(D) Adaptive Radiations often occur after extinctions because of available niches, or when a group colonizes a novel niche (habitat).
(E) The Big Five Mass Extinctions are responsible for more than 90% of all species extinctions.

4. Choose the CORRECT sequence of events in the History of Life, based on the fossil record.
(a) Origin of life, oxygen in atmosphere, origin of eukaryotes, appearance of stromatolites, origin of animals, origin of dinosaurs, origin of mammals, appearance of Australopithecines, Cretaceous extinction
(b) Oxygen in the atmosphere, origin of bacteria, origin of eukarya, multicellularity, origin of animals, the invasion of land, Cretaceous extinction, origin of mammals
(c) Origin of life, oxygen in the atmosphere, origin of eukaryotes, origin of animals, the invasion of land, origin of reptiles, appearance of mammals, extinction of dinosaurs (except for birds)
(d) Origin of bacteria, oxygen in atmosphere, origin of eukaryotes, the invasion of land, evolution of hox genes and radiation of animal body plans, origin of dinosaurs, origin of mammals, appearance of Australopithecines
(e) Oxygen in the atmosphere, origin of eukaryotes, evolution of multicellularity, origin of dinosaurs, Permian extinction, origin of mammals, Cretaceous extinction, origin of birds

5. Which of the following is TRUE regarding events of the Cambrian Explosion?
(a) According to genetic data, radically new animal body plans appeared suddenly and within a short time span (within 50 million years), in contrast to fossil data, which suggest a longer radiation
(b) There is clear fossil evidence that a mass extinction of soft bodied organisms preceding the Cambrian Explosion
(c) Only a few animal phyla appeared at this time, such as the arthropods (trilobites) and molluscs
(d) The Cambrian Explosion is characterized by the radiation of radically different animal body plans that we classify into different animal phyla
(e) At this time, there was sudden warming of the planet and extinction of 60-80% of species, allowing the adaptive radiation of diverse animal phyla

6. Which of the following is most TRUE regarding the current 6th Mass Extinction?
(a) The 6th mass extinction is likely to be followed by adaptive radiations of large bodied organisms and many predators
(b) Studies estimate that current rates of extinction are orders of magnitude higher than the background rate of extinctions
(c) The current 6th mass extinction will result in a much greater number of species going extinct than the total number of species that have gone extinct from background extinctions throughout earth history
(d) Based on fossil data of vertebrates from the previous Big Five mass extinctions, the current rate of extinction is occurring much more slowly than previous mass extinctions
(e) The current mass extinction is unique, as previous extinctions did not coincide with global climate change

Questions
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• How did the Oxygen Revolution come about?
• What are the implications of a high oxygen atmosphere for organismal physiology?
• How were Eukaryotes created?
• What are animals?
• About when did animals evolve? Is there congruence between fossil estimates versus molecular clock estimates of the timing?
• How did animals diversify (Cambrian Explosion)?
• Where did life evolve (land, sea)?
• About when did organisms begin to live on land?
• What are some challenges of living on land (relative to the sea)?
1. Which of the following is MOST likely to be true regarding evolutionary relationships among the major domains of life?

(A) Bacteria and Archaea are both grouped into the category of "Prokaryotes" because they are more closely related to each other than to Eukaryotes

(B) Archaea are ancestral to all other forms of Life

(C) The Oxygen Revolution defines the emergence of life on Earth

(D) Eukaryotes arose from a symbiotic relationship among prokaryotes

(E) Eukaryotes evolved from Prokaryotes through Horizontal Gene Transfer

2. Which of the following is Least likely to be true regarding Prokaryotic Metabolism and the Oxygen Revolution?

(A) The oxygen revolution led to the proliferation of diverse types of prokaryotic metabolism

(B) The oxygen revolution enabled the preponderance of more efficient metabolism that could produce more ATP per unit glucose

(C) The oxygen revolution altered the atmosphere of the Earth

(D) The oxygen revolution created an inhospitable habitat for many classes of prokaryotes that use molecules other than oxygen as their terminal electronic acceptor for energy production

(E) The oxygen revolution was caused as a byproduct of photosynthetic activity of cyanobacteria

3. Which of the following does NOT make RNA a good candidate for early life on earth?

(a) RNA could act as an enzyme

(b) RNA could serve as the genetic code

(c) RNA is much more stable than DNA in our current atmosphere

(d) RNA can catalyze chemical reactions that break or synthesize phosphodiester bonds in RNA or DNA

(e) Recent studies suggest that RNA is capable of self replication

4. Which of the following is NOT a consequence of the Oxygen Revolution?

(a) The ability of organisms to metabolically produce more ATP by using oxygen as the terminal electron acceptor during respiration

(b) Eukaryotes, which evolved after the Oxygen Revolution, all use aerobic metabolism

(c) The transformation of the earth’s atmosphere ~2.5 billion years ago from one that was chemically reducing to one that is oxidizing

(d) The heightened risk of DNA and cellular damage in organisms through oxygen free radicals

(e) The proliferation of bacteria that use oxygen as the terminal electron acceptor during respiration, such that nearly all bacterial species are aerobic

Answers

• 1D
• 2A
• 3C
• 4E