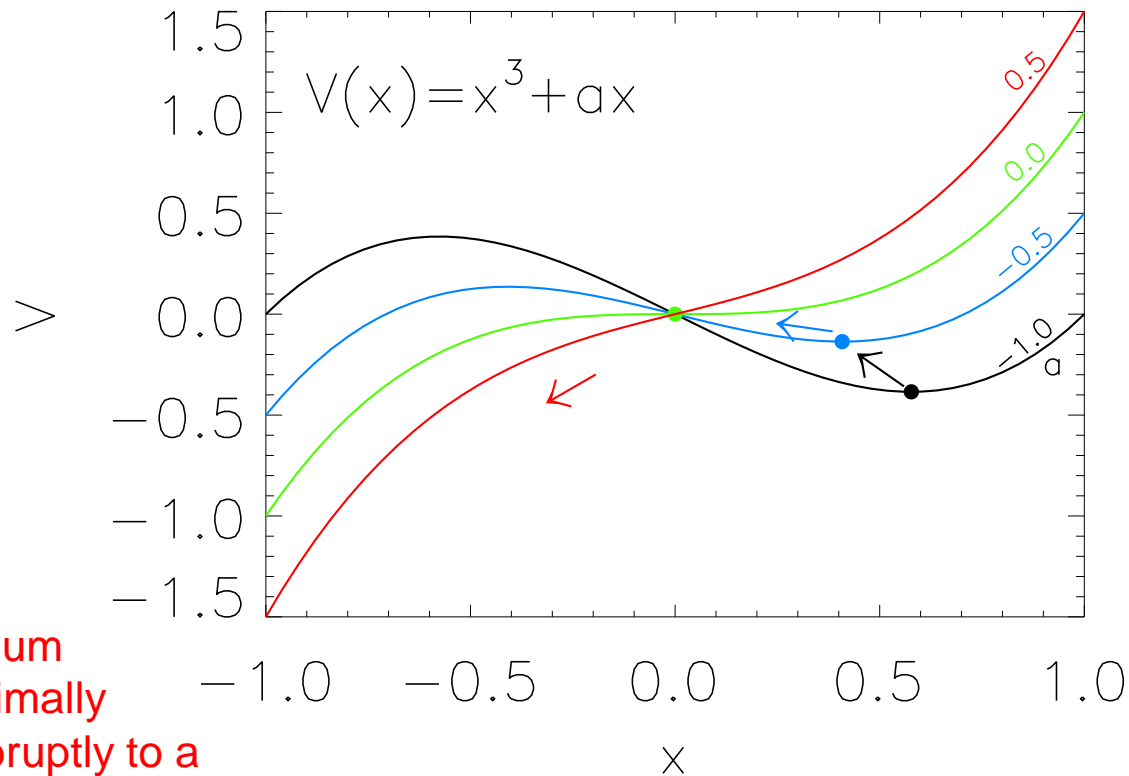


Development of Complexity

Catastrophe Theory

- Consider a potential function $V(x) = x^3 + ax$.
- When $a < 0$ there is both a stable minimum (dots) and an unstable maximum in the potential.
- As a is slowly increased, the equilibrium system moves smoothly to smaller x :
$$x_{eq} = \sqrt{-a/3}.$$
- When $a = 0$, the stable minimum disappears, and for a infinitesimally positive, the system moves abruptly to a new equilibrium very far removed from the old.



Boolean Networks

A logical system composed of units or nodes that can be in either on or off states (analogy, lightbulbs). One could have a system of N nodes, each connected to K other nodes. Whether a node is on or off is determined by the state of the connected neighbors and a set of logical rules. For example, suppose $K = 2$, so that node A is connected to nodes B and C, and the logical rules are: if B and C are both on or off, then A is turned on. If B is on and C is off or vice versa then A is turned off. Beginning from an initial state, the network takes a step and alters the state of each node, if necessary, to comply with the logical rules.

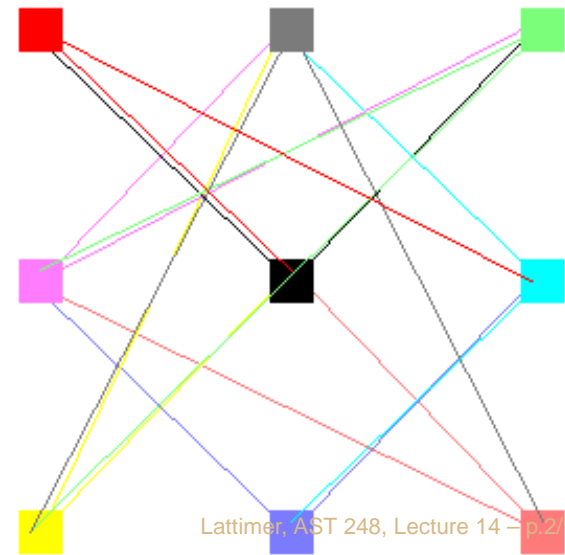
Since some state of the network will eventually repeat an earlier state, the system will eventually enter a repeating cycle. The length of the cycle could be as short as one step (*i.e.* the system is fixed) or extremely large. A large network will seem to behave chaotically.

In between these extremes, Boolean networks show interesting behavior, such as quickly reverting to cyclical behavior, known as an attractor. For example, if

$N = 100,000$ and $K = 2$ there are about $\sqrt{N} = 316$ different cycles, each about 316 steps long. This is surprisingly orderly behavior: out of the

$10^{30,000}$ possible states, it will end up in one of these 316 cycles. Thus the vast majority of the system's possible states are never visited after the limit cycle is obtained.

As the network goes into a limit cycle, about 70% of the nodes become frozen, with the other 30% randomly varying. When the frozen sea forms marks a phase transition between chaos and order.



Stuart Kauffman has applied this model to genes to describe genetic regulatory networks and to the development of complex organisms. He examines how one goes from an undifferentiated egg by repeated cell division to differentiated cell types: red blood cells, retinal cones, etc. Genes are the nodes of a Boolean network and cell types are the attractors or limit cycles; cell division represents a timestep. He reasons that cell specialization is obtained for free from the connectivity rules. The number of genes in humans is about 100,000 and the number of cell types is about 256, close to its square root. This scaling also seems to work for other organisms. Furthermore, about 70% of the genes are permanently turned on in all cell types.

How Small Can Organisms Be?

Smallest bacteria and archaea

- *Carsonella ruddii* contains a circular chromosome of 159,662 base pairs with a high coding density (97%) with many overlapping genes and reduced gene length. Number of predicted genes is 182, lowest in record.
- *Nanoarchaeum equitans* discovered in a hydrothermal vent, about 400 nm in length, and containing 490,885 base pairs. Genes for several vital metabolic pathways are missing; they cannot synthesis nucleotides, amino acids or lipids. But it has DNA repair mechanisms and can carry out DNA replication, transcription and translation.
- *Mycoplasma* is the smallest free-living organism with 580,000 base pairs and 517 genes. Numerous genes essential for life are missing.

Minimal Genome Project

- A study headed by Craig Venter to find the smallest working set of genes necessary for an organism to live and reproduce successfully. *Mycoplasma* was subjected to random gene knockouts, with each knockout mutant being tested for signs of life. Roughly one third of the knockouts that resulted in a non-viable mutant were from genes that had a function that was unknown at the time. About 300 genes seem to be necessary for survival.
- It is also planned to create a synthetic chromosome and inject it into *Mycoplasma* with the original genetic material removed to attempt to create artificial life.
- Intent will be to develop a new fuel or agent for environmental remediation.

Nanobes

- Filamental structures found in rocks and sediments.
- Might be smallest form of life, 10 times smaller than the smallest bacteria, *C. ruddi* (160 kbp) *Mycoplasma* (580 kbp), or archaeum, *Nanoarchaeum* (491 kbp).
- Smallest are 20 nm in diameter.
- Debate concerning if they contain DNA.
- Similar to life-like structures in ALH84001, the Martian meteorite.
- Commercially interesting in plastics manufacturing.
- Recovered from sandstone rock retrieved from 3-5 km under ocean bed where pressure is 2000 atm and $T = 115 - 170^{\circ} \text{C}$.
- Could be implicated in some diseases and calcification of teeth and arterial walls.
- It is suggested this could be a new form of life, but most biologists are doubtful at this stage that they are independent life forms.
- Main argument against, lacking DNA/RNA evidence, is they are simply too small.



Major Stages of Evolution

4.5 Gyr Formation of Earth

3.9 Gyr End of Late Heavy Bombardment of inner solar system

3.85 Gyr First chemofossil evidence of life (disputed)
Life was anaerobic, chemoautotrophs, utilize H₂S

3.5 Gyr First microfossil evidence, first evidence for photosynthetic life
First photosynthesizers utilized H₂S.

2.7 Gyr Cyanobacteria develop aerobic photosynthesis using H₂O

2.4 Gyr Buildup of O₂ in atmosphere, avoidance of “Oxygen Catastrophe” Development of Eukaryota through endosymbiosis (mitochondria and chloroplasts); nuclear membranes, organelles, sexual reproduction, flexible cell walls, internal scaffolding (cytoskeleton).

Perhaps connected with large bacteria Magnetobacter with organelles of magnetite (Fe₃O₄), connection to development of Earth's core and magnetic field at the same time. enables identical DNA replication, 1000-fold DNA size increase

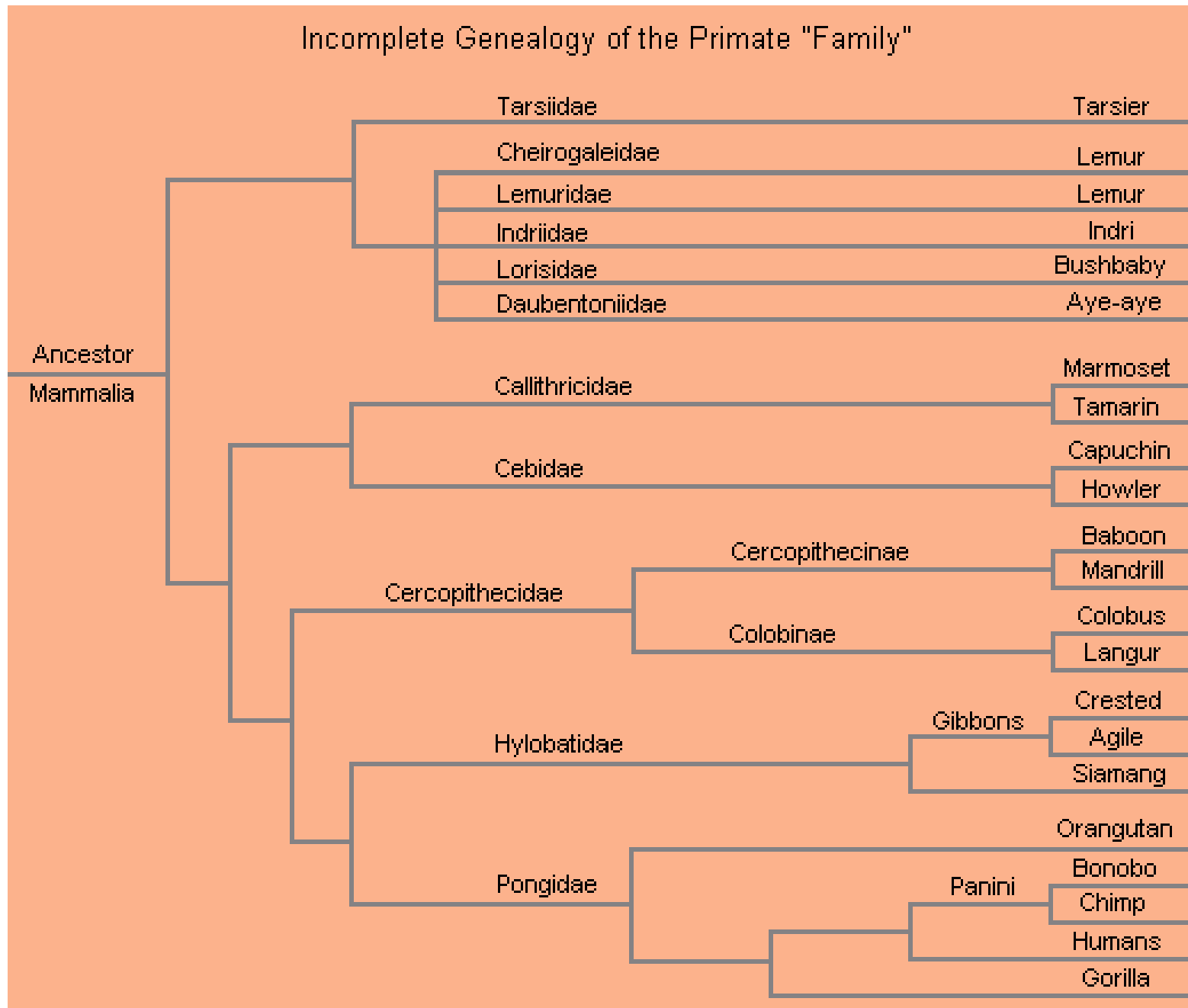
1.2 Gyr Earliest evidence for multicellular organisms, including animals and plants

545 Myr Cambrian Explosion leading to proliferation of animal diversity over a 40 Myr period.

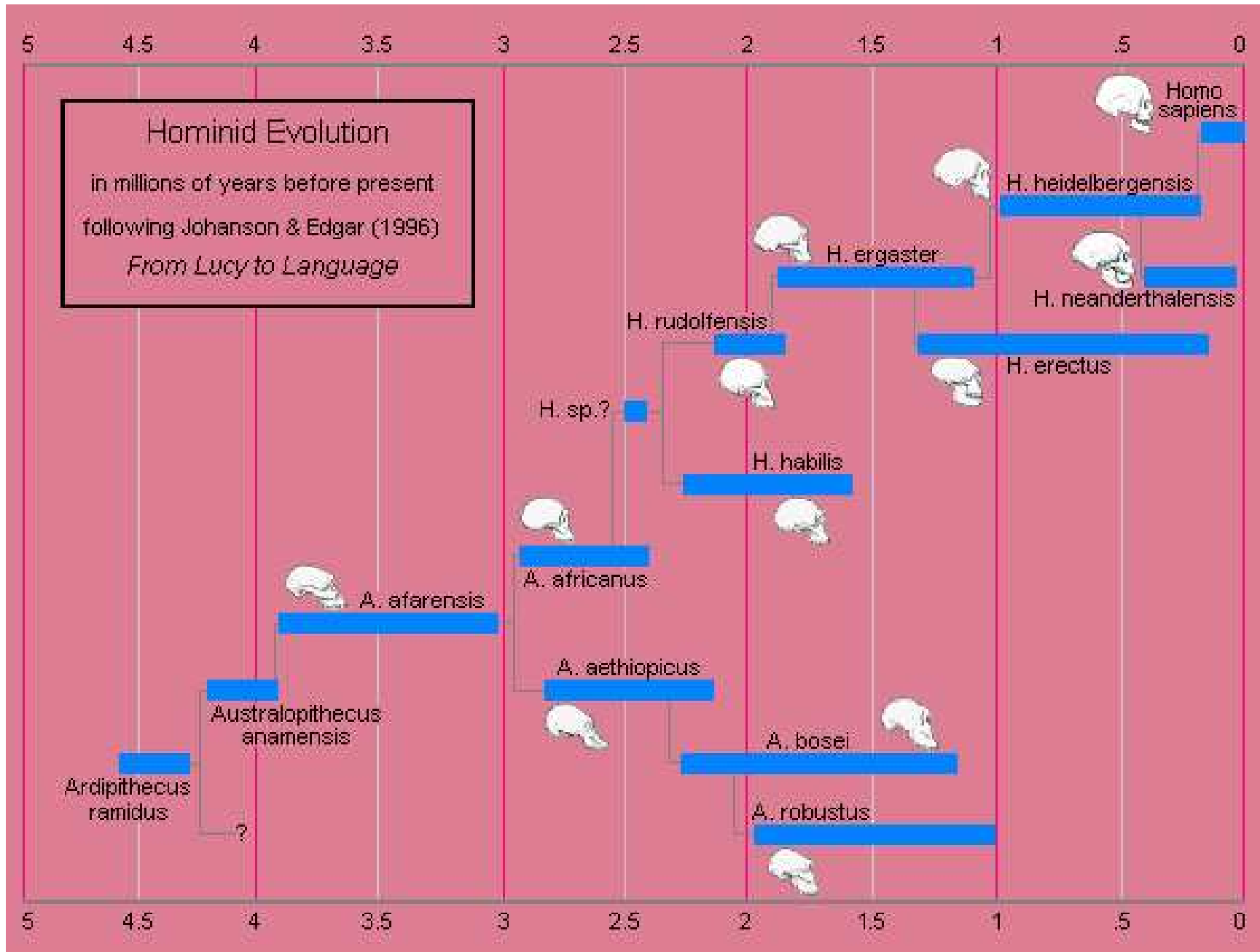
Only major period of family diversification in geologic record. Causes: O₂ levels, genetic complexity, Snowball Earth, absence of predators.

- 475 Myr** Plants develop means to live on land, evolving from algae.
- 440 Myr** First major extinction (Late Ordovician)
- 400 Myr** Amphibians and insects colonize land.
- 360 Myr** Dense Carboniferous forests, resulting in coal and oil.
- 250 Myr** Permian extinction leading to dinosaur domination
- 210 Myr** Late Triassic extinction
- 200 Myr** First charcoal observed in strata, evidence that O₂ levels are near present values.
- 65 Myr** K-T extinction of dinosaurs leading to mammalian domination
- 60 Myr** Last common ancestor of primates
- 7 Myr** Hominid develops, last common ancestor of humans, gorillas and chimpanzees
- 0.2 Myr** First human (*Homo sapiens*) fossils
- 0.05 Myr** Upper Paleolithic Revolution and exosomatic symbols and projectile weapons: emergence of true intelligence?
- 0.03 Myr** Extinction of Neanderthals
- 0.012 Myr** Extinction of *Homo floresiensis*

Primate Evolution



Hominid Evolution



Adam and Eve

The most recent common ancestor of all currently living humans can be traced by matrilineal and patrilineal paths, effectively tracing the family tree backward in time. Eventually, the lineages converge.

- Matrilineal: mitochondrial DNA (mtDNA) traces the Mitochondrial Eve. Seems to have lived about 140,000 years ago in Ethiopia, Kenya or Tanzania, using the molecular clock technique of correlating elapsed time with observed genetic changes.
- Patrilineal: Y-chromosome traces the Y-chromosomal Adam. Seems to have lived about 60,000 – 90,000 years ago in Africa using molecular clock and genetic marker techniques.

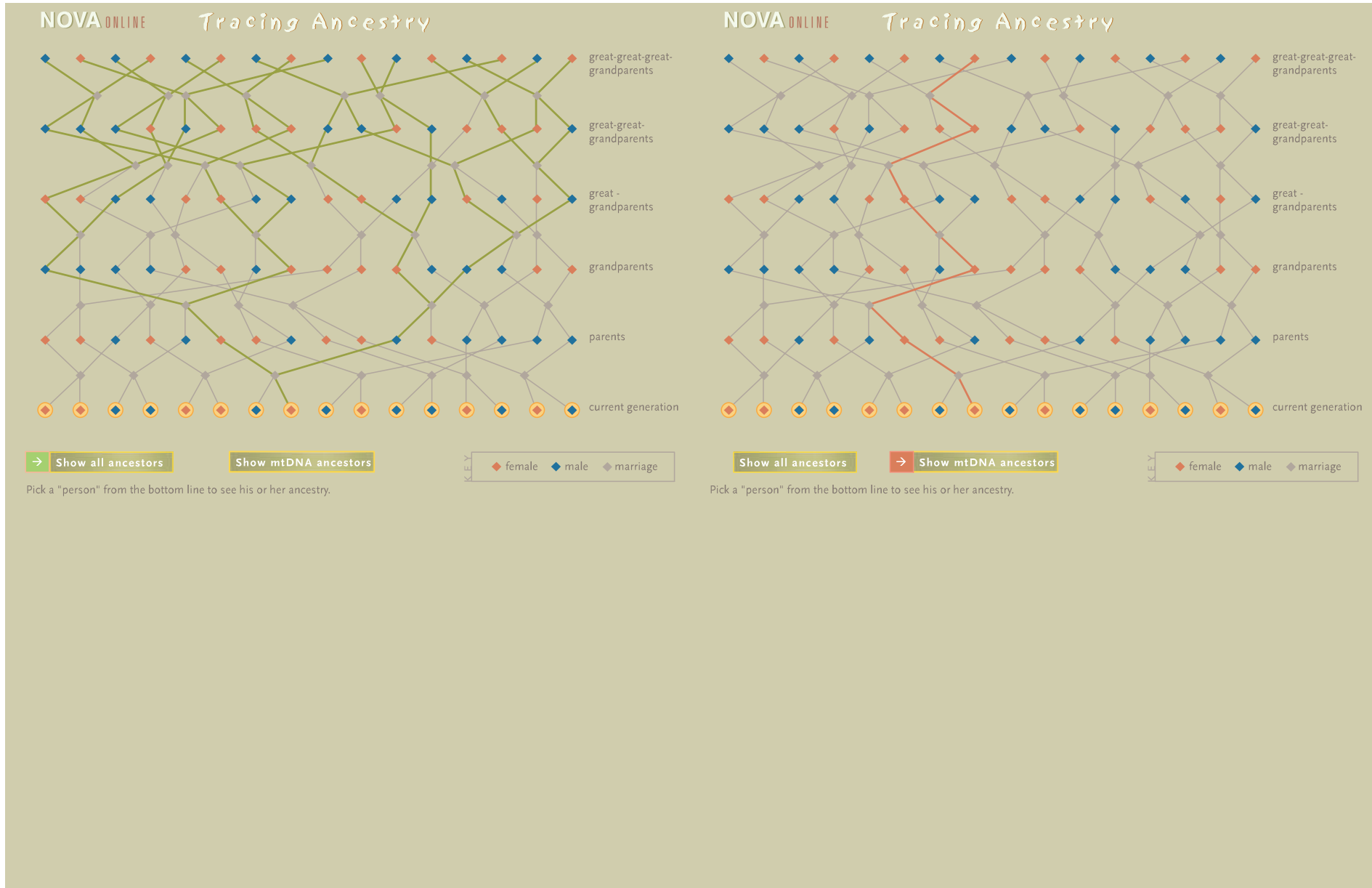
Both female and male most recent common ancestors lived much longer ago than the most recent common ancestor, estimated to be as recent as 1500 years ago.

The identical ancestors point, between 4000 and 10,000 years ago, is where all humans can be divided into two groups: those who left no descendants today and those who are common ancestors of all living humans.

Ancestry

- The number of your ancestors must increase as you go back into the past. The same is true for everyone. However, the number of humans on the Earth decreases as you go into the past. There is a higher likelihood, as you go into the past, of finding an individual who was an ancestor of any random person alive today. Go back far enough, and it becomes a certainty: this was the most recent common ancestor (MRCA).
- **Proof that Mitochondrial Eve (or Y-chromosomal Adam) exists:** All humans alive today form the set S . The set of all women who were mothers of the members of S is S' , and the size of S' must be no larger than the size of S (each of us has only 1 mother). But it is more likely that the size of S' is much smaller than the size of S (each woman typically has more than 1 child).
- Repeat the process to set S'' and so on: each succeeding set is smaller than before. Finally, the set S'^* will contain 1 woman.
- This woman was not the only woman alive then; she had many contemporaries. But none of them left descendants along the matrilineal line.
- Once a mitochondrial Eve is established, further births cannot change her title. But further deaths can shift the mitochondrial Eve to a later individual. This happens, for example, during a population bottleneck (e.g., a plague reduces enormously the number of humans).

MRCA



Evolution of Information Capacity

DNA and Information

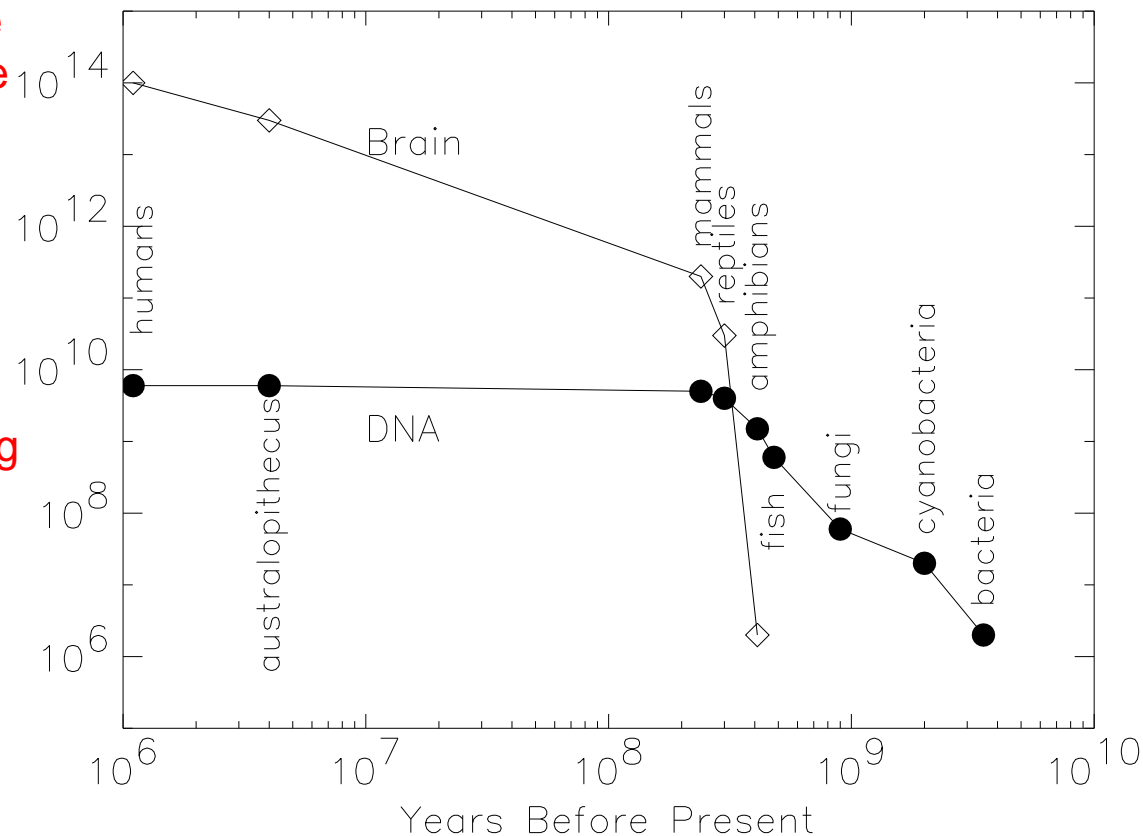
DNA carries information in a computer-like way. Each base-pair contains two bits of information (The prior uncertainty is the number of equiprobable alternatives $N = 4$, so the information content of a message that narrows those alternatives down to 1 is $\log_2 N = 2$.) We will use the genome length to measure the information content, but note that this can be misleading:

- Much of the human genome, as well as other complex organisms, contains junk DNA that does not seem to contain useful information. It does not contribute to information content. In humans, the useful DNA is a mere 2% of the total. Amoebae have a genome 80 times that of humans but a considerably smaller percentage is useful coding.
- Conversely, DNA contains additional information to that contained in a simple reading of base-pairs because genes are often regulated by the activation of several other genes in a regulatory network.

Information and the Nervous System

The nervous system, especially the brain, also contains information, but the storage is more complicated.

- The brain contains 10 billion neurons, each connected to between 1000 and 10,000 others.
- The position of the neurons is the least of the information. To get a 1 part in a billion accuracy, you need about 90 bits per neuron or a total of 120 Mbytes (1 byte = 8 bits).
- The main information is in the connections. We will need the address of each neuron: 10 billion can be stored with 34 bits ($2^{34} = 17$ billion), plus an additional bit to specify the on/off state of each. Each synapse involves at least 1000 neurons bringing the total to 35,000 bits per synapse. There are $10^{10} = 10$ billion synapses, involving a total of $3.5 \cdot 10^{14}$ bits or nearly 0.05 petabytes.



Information and Evolution

- Initially, DNA was limited by error-rate during reproduction to around 10 million base-pairs.
- Error-correcting enzymes (proteins) evolved to increase the length of DNA by about 100.
- Increased specialization of cells accounts for an increase of another factor of 10 in genome length.
- Ultimately, DNA length is limited by chemistry to its present length.
- At the same time this limitation was reached, an alternative method of storing information developed, involving the nervous system.
- Nervous systems quickly evolved into brain stems and brains.
- The multiple-connectivity of neurons vastly increases information storage.
- No one can deny that by any method of measurement there has been a broad overall trend toward increased information content.
 - But is a trend observed in all evolutionary lineages? No, parasites are a good example. It might be that even a majority of lineages have no progressive trend.
 - In those lineages that show progressive trends over long times, there are many reversals and re-reversals in the shorter term, so that the progress is undermined.

Why does information content increase during evolution? A consequence of natural selection.

- Random genetic error (mutations), sexual recombination and migratory mixing all increase genetic variation, the available alternatives, so they decrease the available information content.
- Natural selection is a winnowing of the available alternatives, and thus increases the information content.
- Natural selection is thus nonrandom in the direction of improvement (survivability and reproductivity).
- Relatively small changes in the genome have produced major differences in organisms. The chimpanzee genome differs from a human's by about 2%.

A qualitative change in intelligence accompanied small quantitative increase.

Big brains, tools (chimpanzees, elephants, ravens), culture and linguistic abilities (apes, whales, dolphins) and self-awareness (elephants, dolphins, apes) aren't uniquely human.

The key step might have been the development of projectile weapons and exosomatic symbols: symbolic intelligence (messaging without direct use of body – decorated clothing, jewelry, paintings, ornate weapons).

Further dramatic increases in information capacity occur because of civilization

- Societal specialization
- Language
- Technology (tools, books, computers)

Evolutionary Implications

- Even at a microscopic level, evolutionary advantages of complex and/or specialized structures imply that they will develop.
- Several significant physical conditions seem necessary for intelligence to develop: land, O₂ atmosphere, relatively stable climate.
- It is a fact of life that major catastrophic events will randomly change the direction and pace of evolution; in our one example, Earth, the net effect has been to enhance evolution because events did not completely extinguish life and new ecological niches were created.
- Major terrestrial-based changes, such as earthquakes, volcanos, continental drift, seem to have a limited or gradual impact. Possible exception: Snowball Earth and the Cambrian Explosion.
- Sudden catastrophic changes seem to be connected to random, extraterrestrial events:
 - Impacts
 - Supernovae
 - Gamma-ray Bursts
- Relatively small changes in the genome produce major differences in organisms. The chimpanzee genome differs from a human's by about 2%.
- Although gorillas and chimpanzees have been evolving separately from humans for the same time span (same common ancestor), they have not become intelligent. Is intelligence the logical outcome of evolution?