

# The Origin of Intelligence

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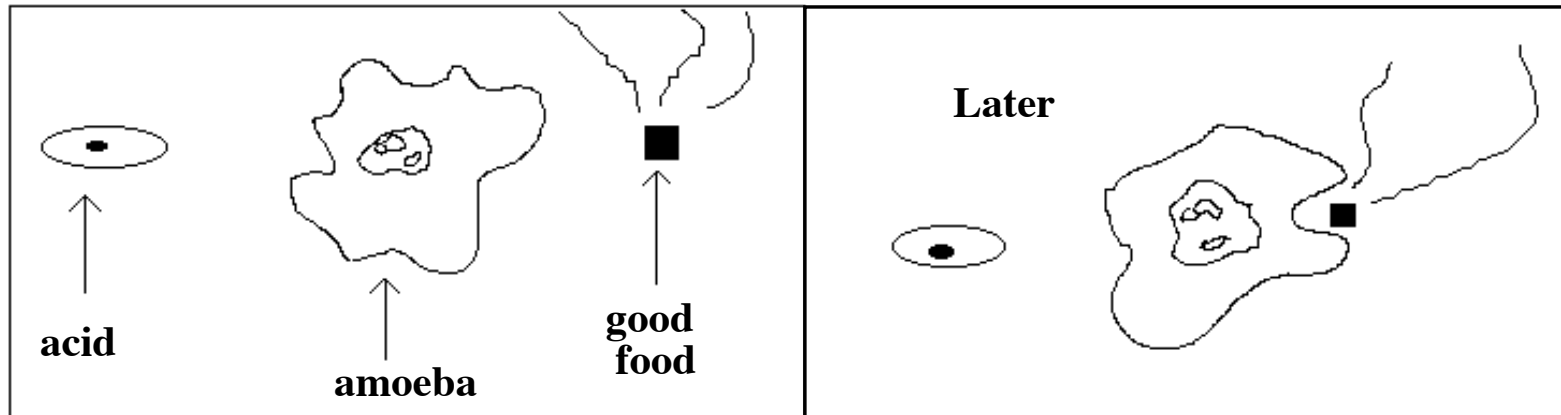
$f_i$  : Fraction of life-bearing planets where  
Intelligence develops

What is intelligence?

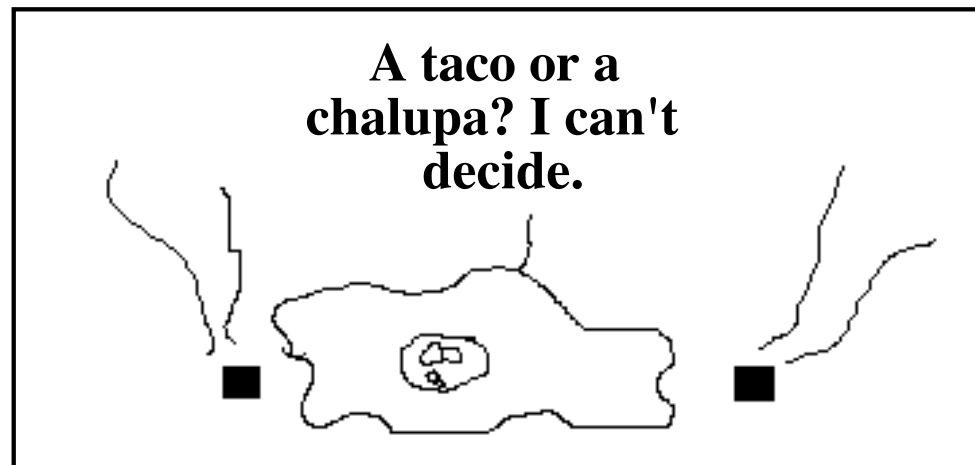
Propose: “The ability to model the world,  
including the organism itself”

⇒ Intelligence as continuum  
related to complexity of organism  
milestone: human-level intelligence

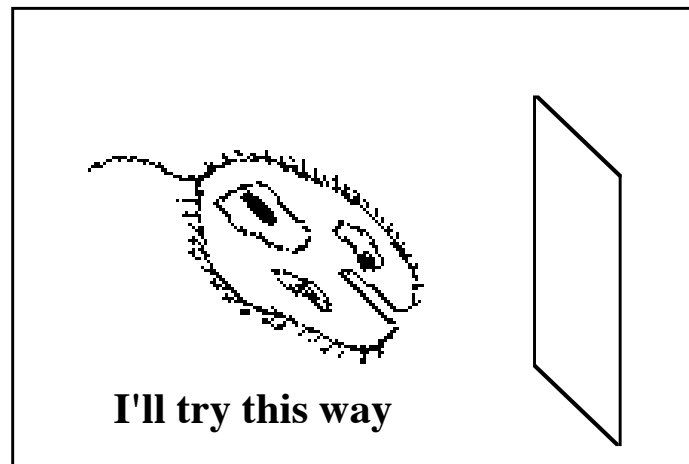
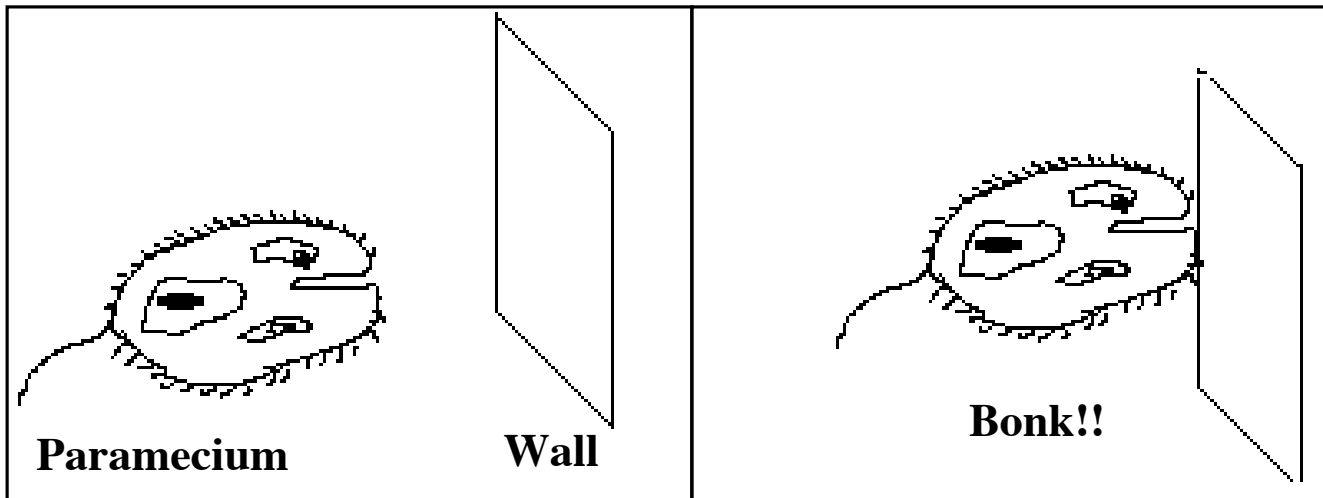
# Amoeba intelligence



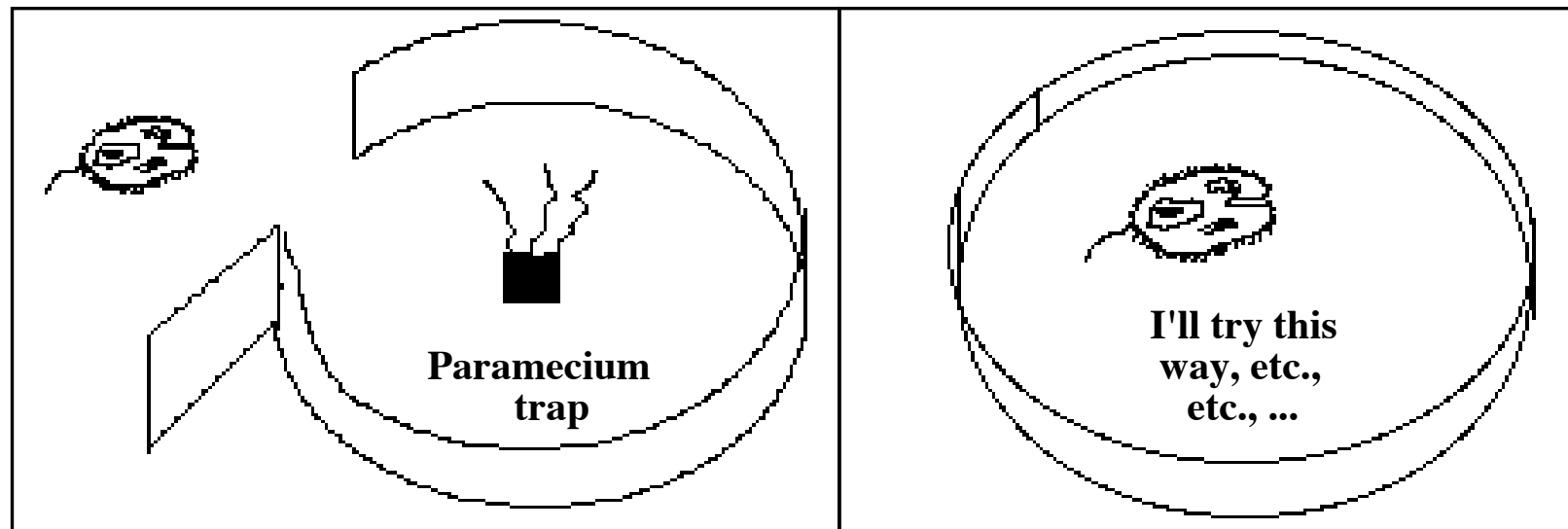
# The Amoeba's dilemma



# The smarter Paramecium



But not THAT smart...



# Information as Measure of Intelligence

Evolution of intelligence  $\simeq$  increase in information

DNA: model of organism, the program

A quantitative measure: # of bits of information

Bit: Information in the answer to a yes/no question

e.g.

Purines

Adenine (A)

Guanine (G)

Pyrimidines

Cytosine (C)

Thymine (T)

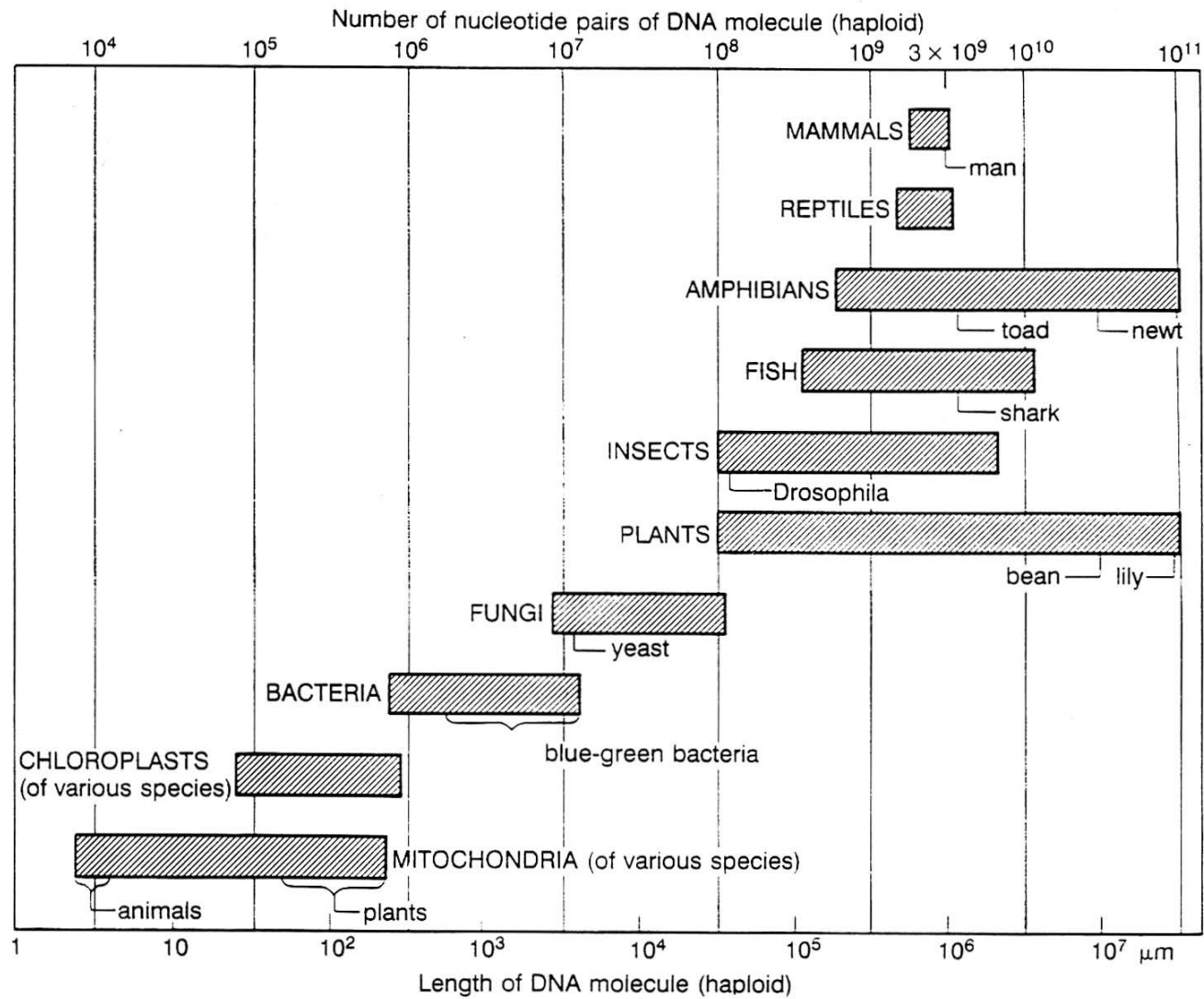
# Information Content

Unit	# of Bits	# of Pages	# of Books
1 base	2		
1 codon	6		
Virus	$\sim 10^3$	1	
Bacterium	$10^6$	1000	
Amoeba	$5 \times 10^8$		500
H. Sapiens <sup>*</sup>	$6 \times 10^9$		small library

<sup>\*</sup>~ 2% codes for proteins

$\Rightarrow 1.2 \times 10^8$  bits





**Figure 7.18.** Length of DNA molecules. Note that the DNA of some plants and amphibians is longer than that of bacteria by a factor of  $10^4$  to  $10^5$ . The total length of human DNA is approximately  $10^6$   $\mu\text{m}$  or 1 m, which is equivalent to roughly  $3 \times 10^9$  nucleotide pairs or  $10^9$  codons. Obviously, the length of DNA carried by an organism is not necessarily related to its phenotypic complexity. We may conclude that DNA does not carry useful information over its entire length. Much of its coding is "nonsense." (Adapted from Alberts, et al. 1983, 405, 530.)

# Evolution produced Increase in information

Caveat:

much of DNA is “non-coding”  $\Rightarrow$  hard to count

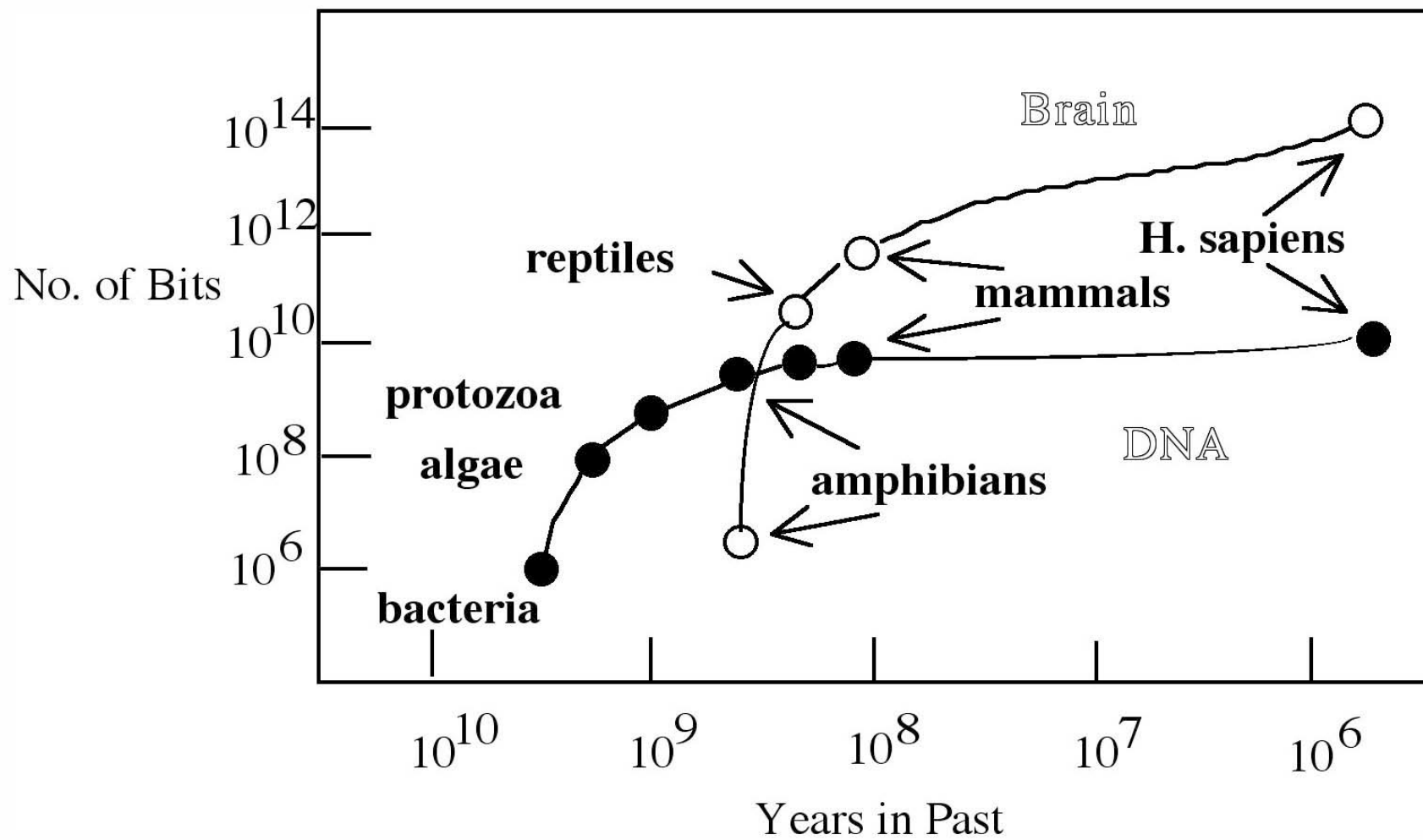
Information stored in DNA limited by fidelity of replication

<u>Organism</u>	<u>Error Rate</u>	<u># of Bits</u>
Virus	$10^{-3}$	$10^4$
Bacterium	$10^{-6}$	$10^6 - 10^7$
Eukaryotes	$10^{-9} - 10^{-8}$	$10^8 - 10^{10}$

Sexual reproduction provides safety measure for mutations in recessive genes

## Further Complications...

- Humans make about 90,000 kinds of protein
- Now it seems we have only 25,000 genes
- What's going on?
- One gene can lead to different proteins
  - The mRNA is edited to remove introns
  - Sometimes exons are left out or introns in
  - Splicing controls gene expression
  - More common in more complex organisms



Based on Sagan  
Dragons of Eden

# Why Brains?

To get more than  $10^{10}$  bits (or  $10^8$ ?), need  
extra-genetic storage

Neurons led to brains

How is information stored in brains?

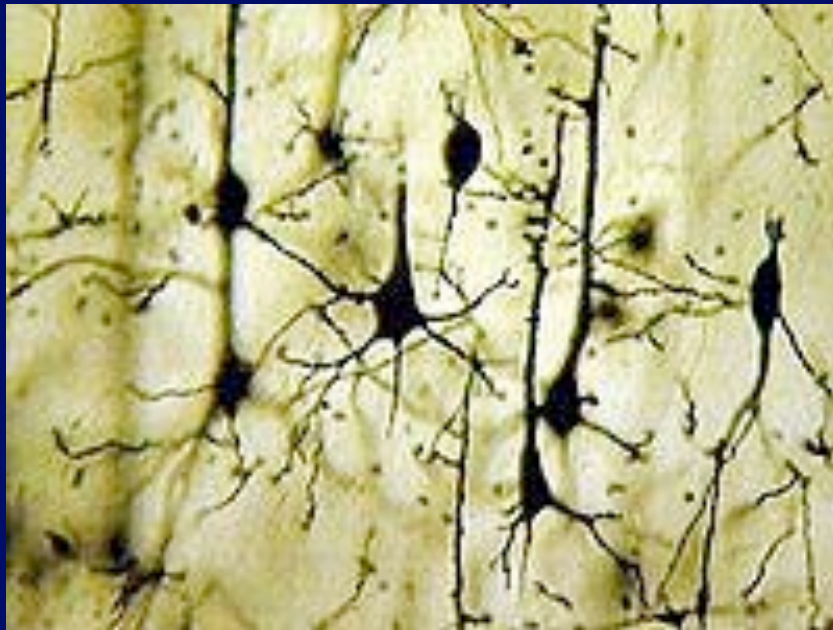
Not entirely clear

Neuron fires or not:

1 bit/neuron

Yes or No

# Neurons are the building blocks



From slice of life project

Neuron has many inputs from dendrites.

Some favor firing, some inhibit firing.

Based on balance, the neuron fires (or not).

Electrical signal travels along axon (output).

Releases neurotransmitters in synapse.

They affect another neuron.

Further complication: reverse signalling.

Receiving neuron can release chemicals that inhibit the neurons that sent “don’t fire” signals. Involved in learning.

# Brains are Different

Neuron firing controlled by many ( $\sim 10^3$ ) inputs -  
synapses

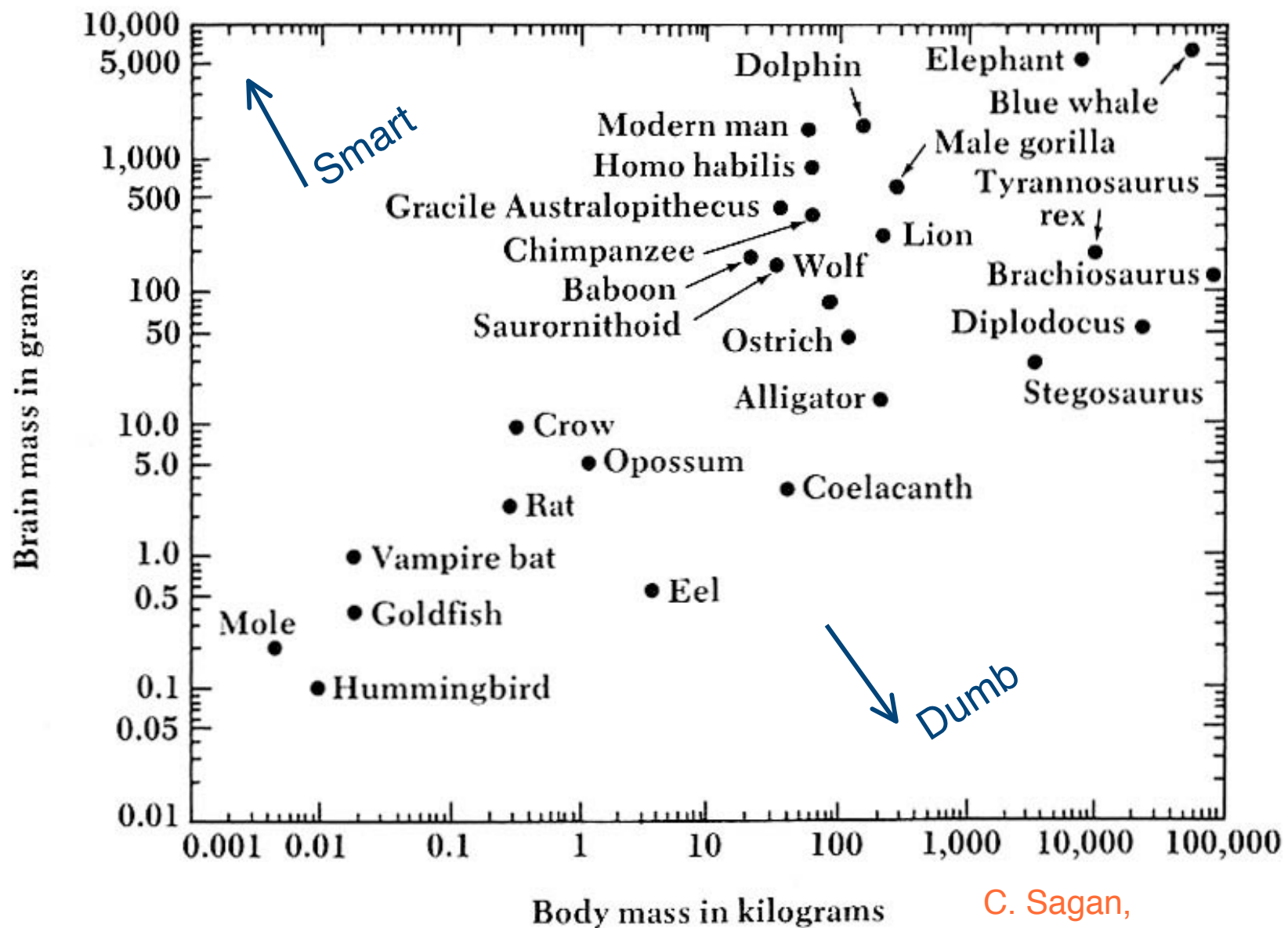
An analog computer  $\Rightarrow$  Hard to count

$\sim 10^{11}$  neurons,  $10^{14}$  synapses

Corresponds to  $20 \times 10^6$  books = NY public library

Surrogate Measure:

Brain size or Brain mass/body mass



C. Sagan,  
Dragons of Eden



# Brain organization

Brain is reprogrammable , unlike genes

⇒ Individual can learn

Two hemispheres

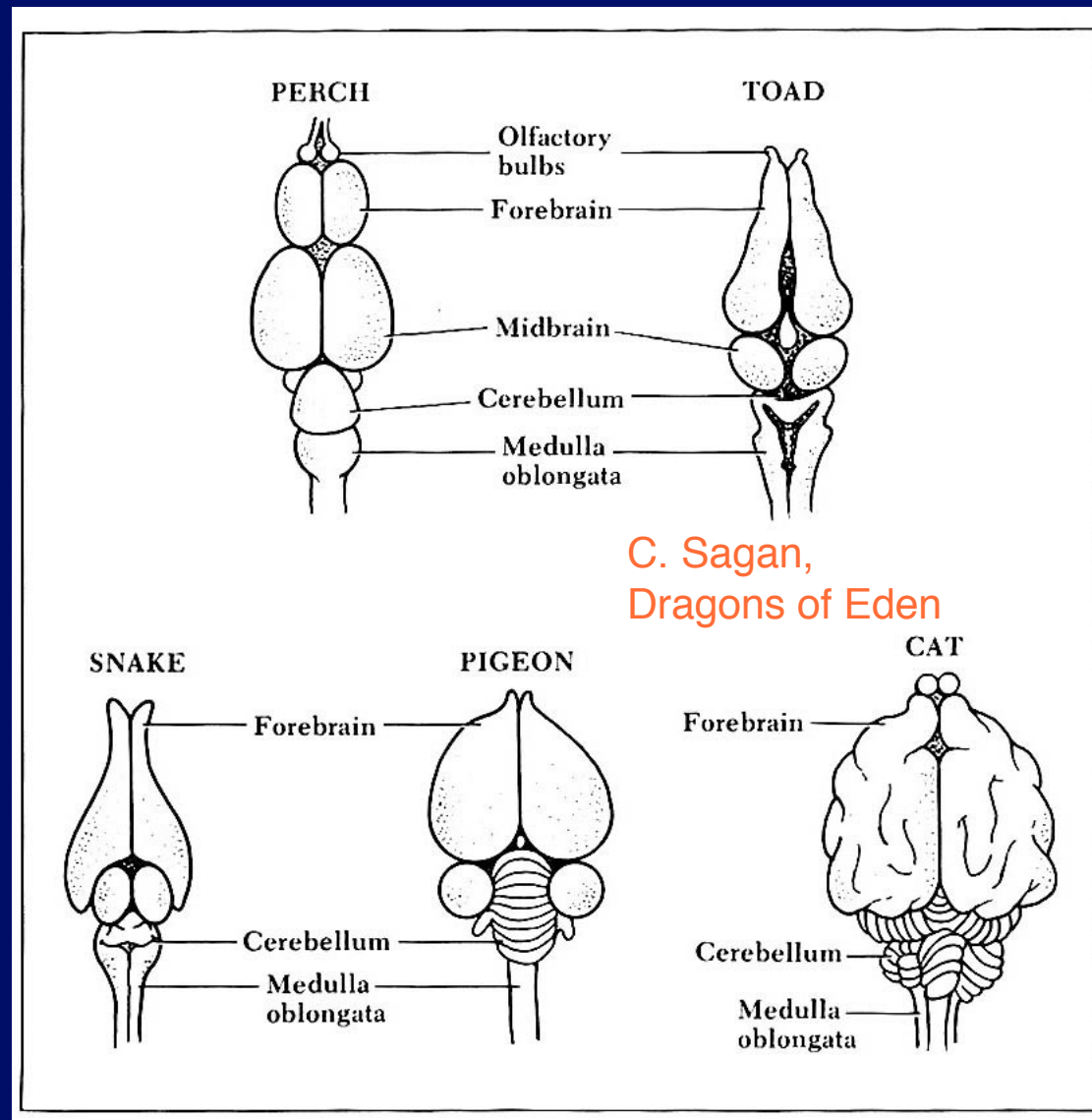
Many functions parallel, but some specialized

Many ways to divide brain

Layered brain:        reptilian brain  
                             limbic system (mammals)  
                             cortex

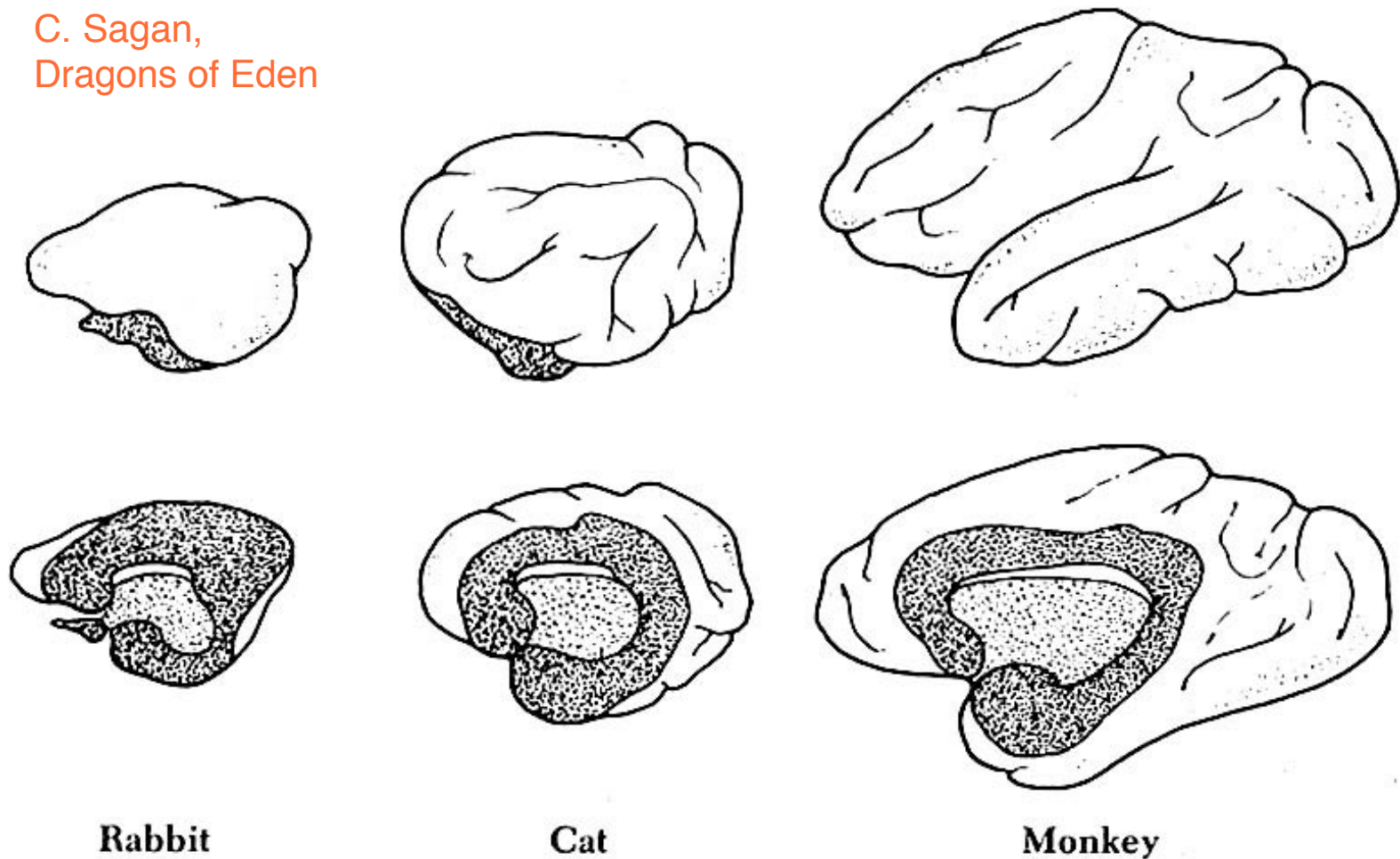
Brain size has increased (in some species) with time

⇒ Evolution favors higher intelligence (sometimes)



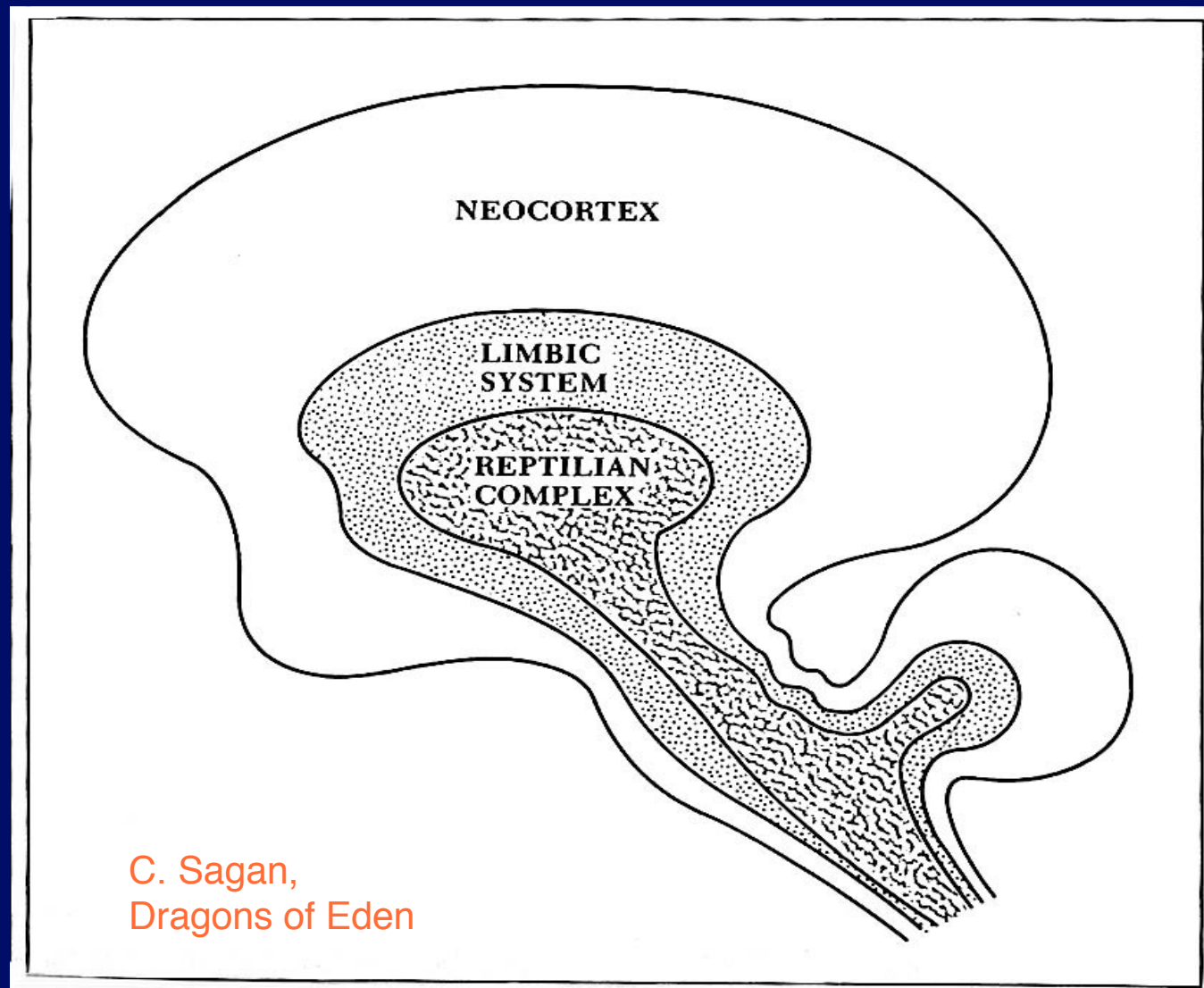
Schematic diagrams comparing the brain of a fish, an amphibian, a reptile, a bird, and a mammal. The cerebellum and medulla oblongata are parts of the hindbrain.

C. Sagan,  
Dragons of Eden

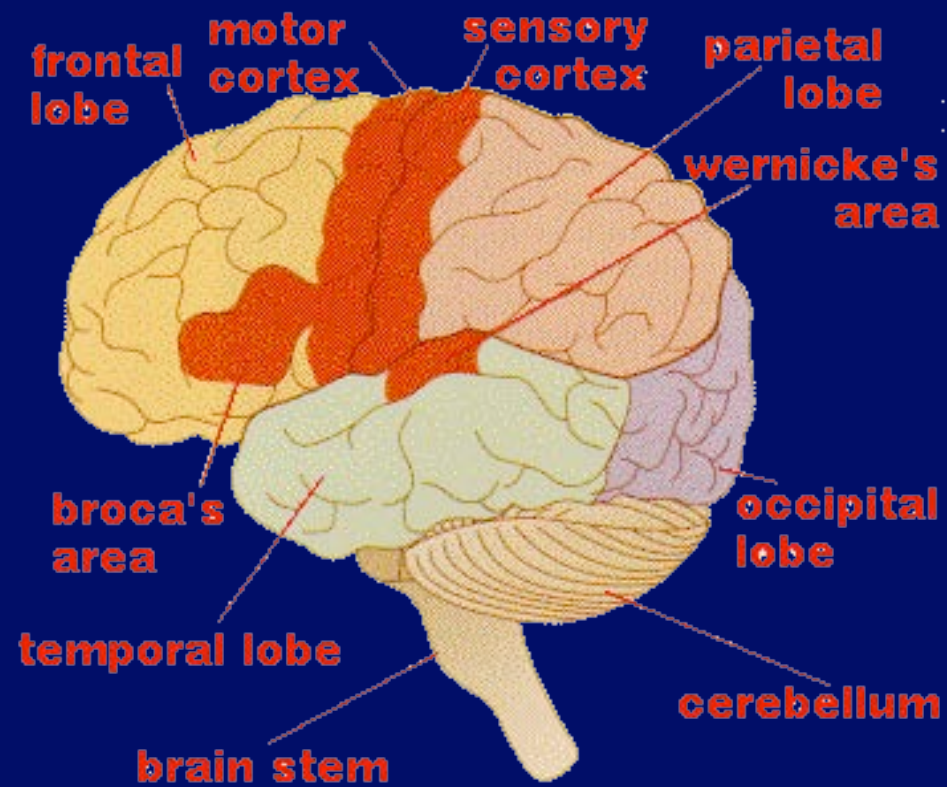


Schematic views from the top and from the side of the rabbit, cat, and monkey brains. The dark stippled area is the limbic system, seen most easily in the side views. The white furrowed regions represent the neocortex, visible most readily in the top views.

A highly schematic representation of the reptilian complex, limbic system and neocortex in the human brain, after MacLean.



# The Big Brain



# Human Evolution

Phylum: chordata - vertebrates - bilateral sym.

Class: mammals arose in Triassic period

~ 225 Myr ago

Proliferated and “radiated” at end of cretaceous  
(~ 65 Myr ago) after extinction of dinosaurs

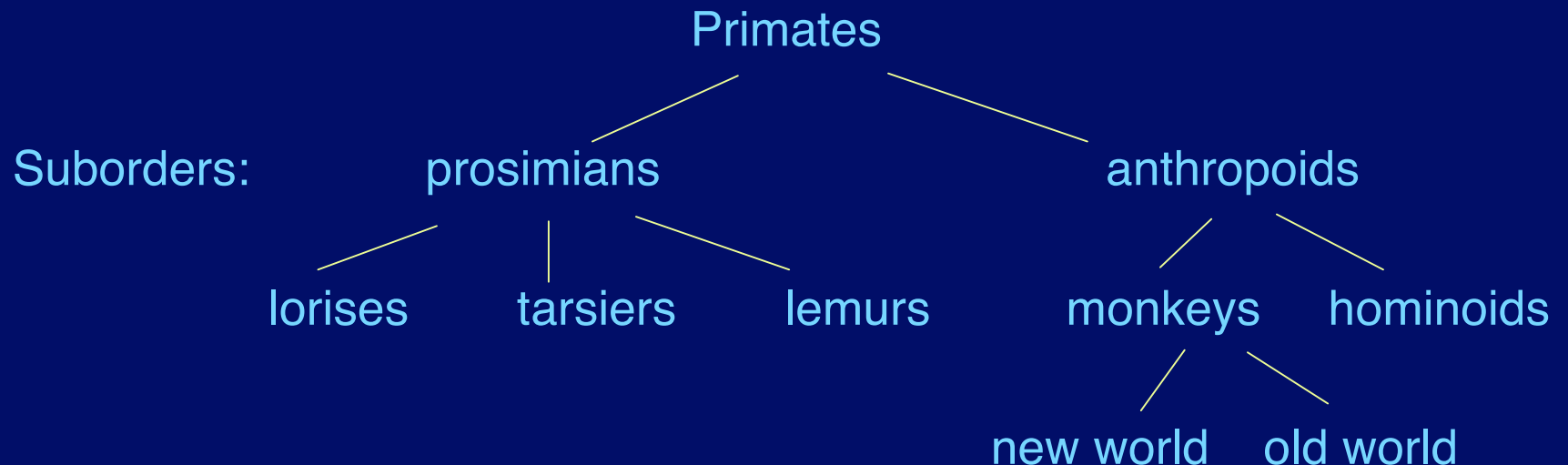
Order: primates - late cretaceous ~ 80Myr ago

# Primate Characteristics

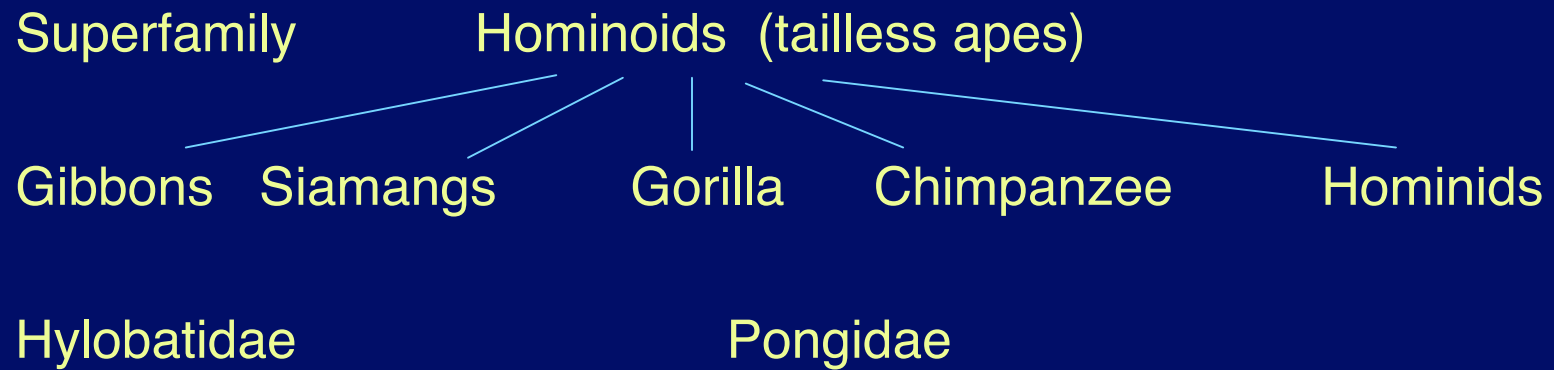
Few anatomical specializations

Flat fingernails, eyes in front

Adapted to life in trees



# The Hominoids





## “Recent” fossil record

Cenozoic Era (recent life)

divided into Tertiary (3rd stage) and  
Quaternary (4th stage) Periods

Tertiary further divided into 5 epochs  
as follows: - dates (in million yrs. ago) are  
rough.

Era	Period	Epoch	Time at beginning (Myr ago)	Events, Fossils of Note
Cenozoic	Quaternary	Recent	5000 yrs	Historical Records Homo sapiens Homo erectus
		Pleistocene	1.8–2.5	Homo habilis
			4.2	Australopithecus
			5.5	Ardipithecus
		Pliocene	6–7	Sahelanthropus
	Tertiary	Miocene	23–26	Gap
				Ramapithecus
				Dryopithecine Apes
		Oligocene	37–38	Gap
				Aegyptopithecus
Mesozoic	Cretaceous	Eocene	54	Tarsiers
		Paleocene	65	Lemurs Tree Shrews - Primates Proliferation of Mammals Origin of Many Orders

# Early Primate Evolution

# Adapting to life in trees

Claws —→ nails, grasp branches  
independent big toe, thumb

Nocturnal  $\longrightarrow$  diurnal

Smell → vision stereo vision  
(eyes in front)

# Color vision

More complicated information processing, tool use becomes possible

# Origin of Anthropoids

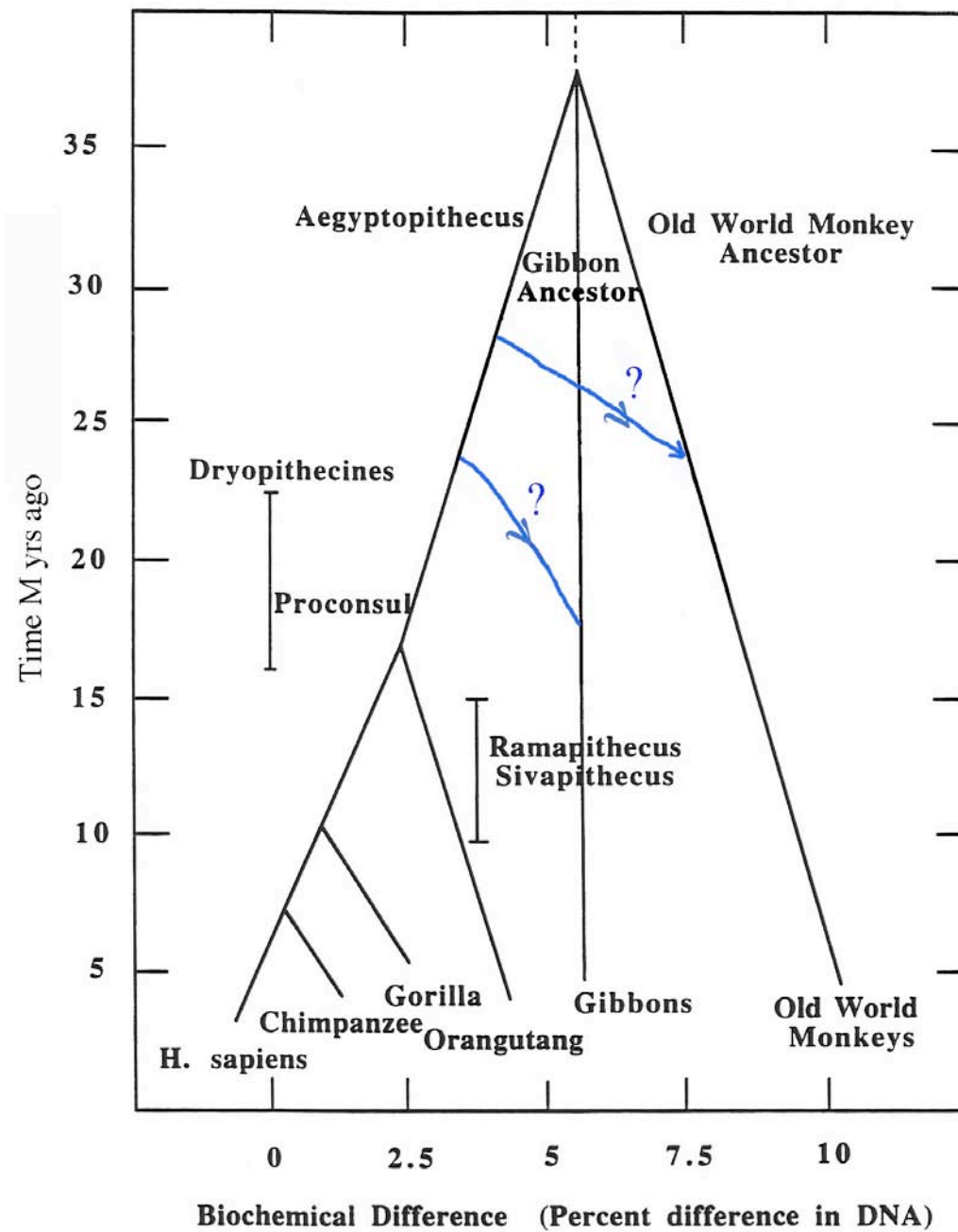
Eocene transition to oligocene ~ 37 Myr ago  
cooler, more grasslands

More diurnal, some leave trees, lose tail

Fayum beds - Egypt 33 Myr ago

Early anthropoid fossil: aegyptopithecus

Used to be considered first hominoid, but now  
suspect monkey/ape split was later



# Hominid Evolution

Fossils now known back to ~ 6 Myr

Molecular dating of chimp - hominid split 5-7 Myr

Many variations now known

many species co-existed in Africa

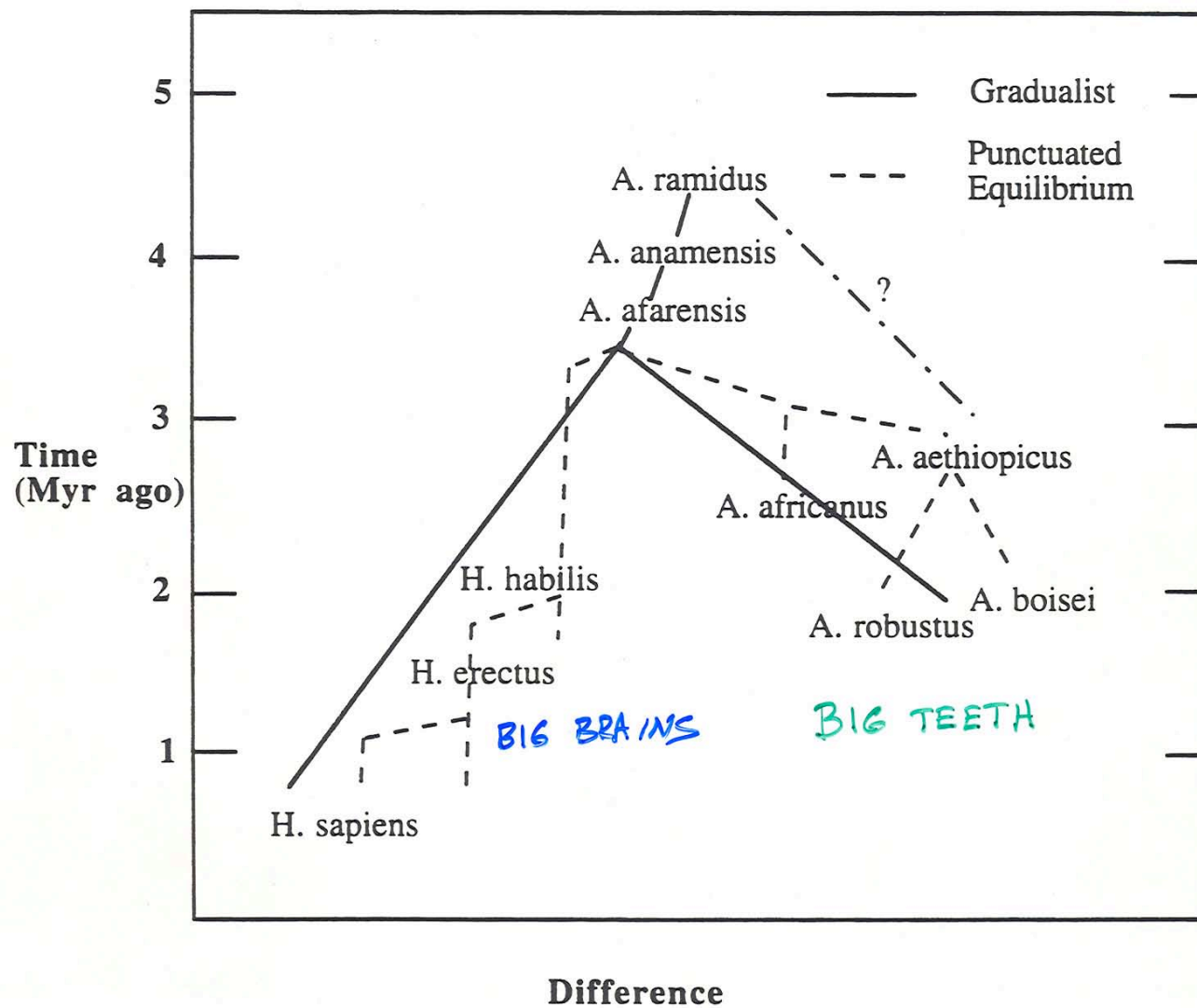
Earlier species show mosaic of human-ape traits

Upright walking preceded brain growth, tool making

May not have arisen on savanna

Looks like “radiation”: many species arising

All but one extinct now



The last 4.5 Myr of hominid evolution are summarized in the accompanying figure. The solid lines in the figure indicate the lines of descent in a gradualist picture, while the dashed lines indicate the picture of punctuated equilibrium.



# Hominids in Africa

RECENT FINDS from Africa could extend in time and space the fossil record of early human ancestors. Just a few years ago, remains more than 4.4 million years old were essentially unknown, and the oldest specimens all came from East Africa. In 2001 paleontologists working in Kenya's Tugen Hills and Ethiopia's Middle Awash region announced that they had discovered hominids dating back to nearly six million years ago (*Orrorin tugenensis* and *Ardipithecus ramidus kadabba*, respectively). Then, last July, University of Poitiers

paleontologist Michel Brunet and his Franco-Chadian Paleoanthropological Mission reported having unearthed a nearly seven-million-year-old hominid, called *Sahelanthropus tchadensis*, at a site known as Toros-Menalla in northern Chad. The site lies some 2,500 kilometers west of the East African fossil localities. "I think the most important thing we have done in terms of trying to understand our story is to open this new window," Brunet remarks. "We are proud to be the pioneers of the West."

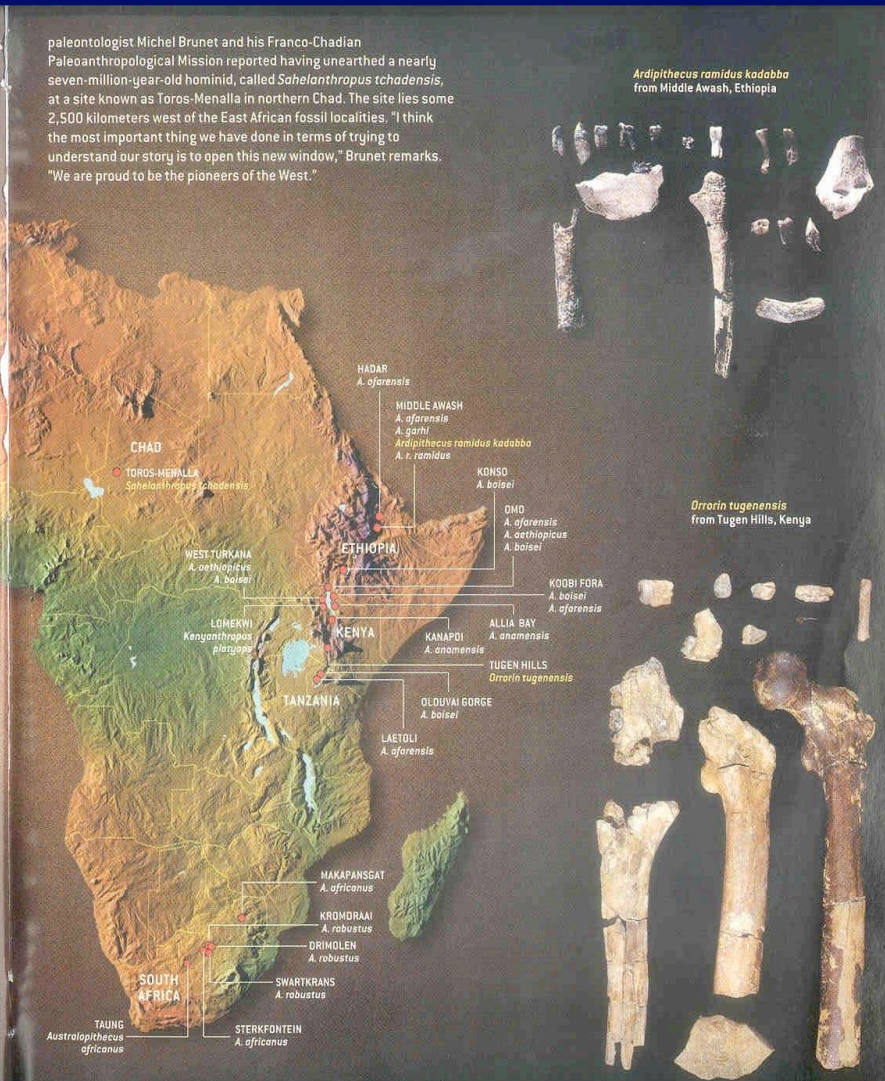
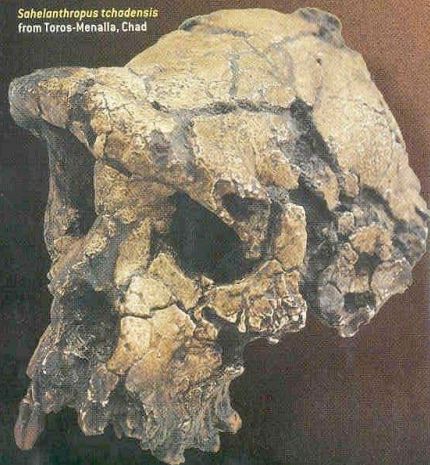
*Ardipithecus ramidus kadabba*  
from Middle Awash, Ethiopia



*Orrorin tugenensis*  
from Tugen Hills, Kenya



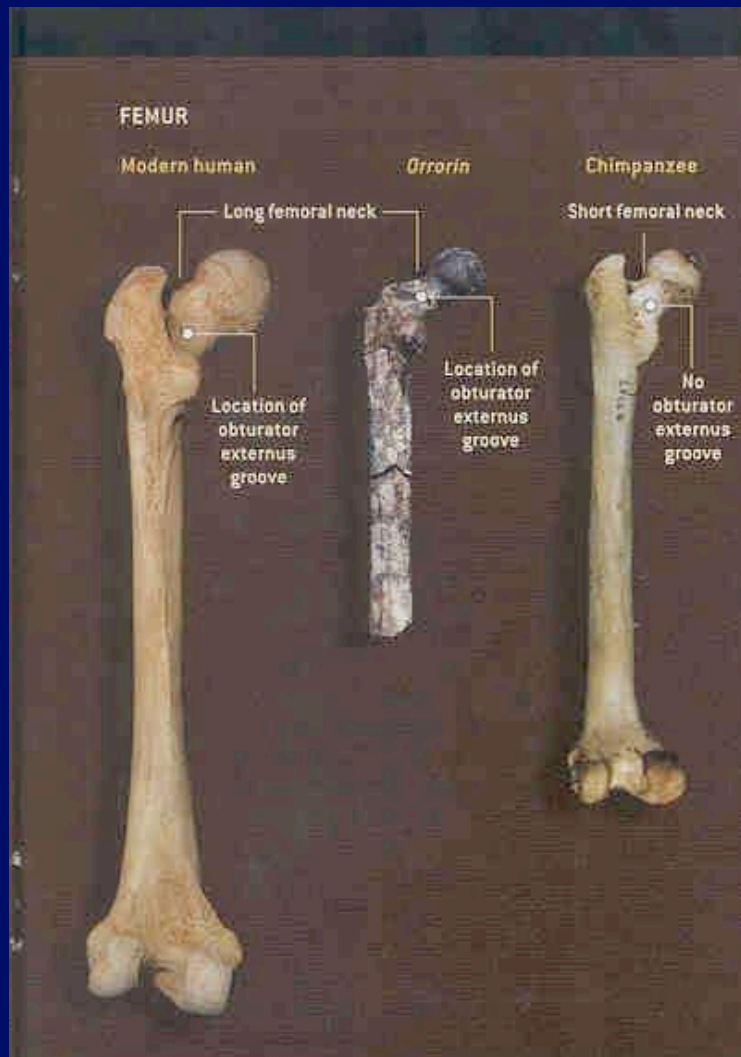
*Sahelanthropus tchadensis*  
from Toros-Menalla, Chad



Scientific  
American  
Jan. 2003



# Comparison of Femurs



Femur adapted  
to bipedality  
already by 6 Myr  
ago

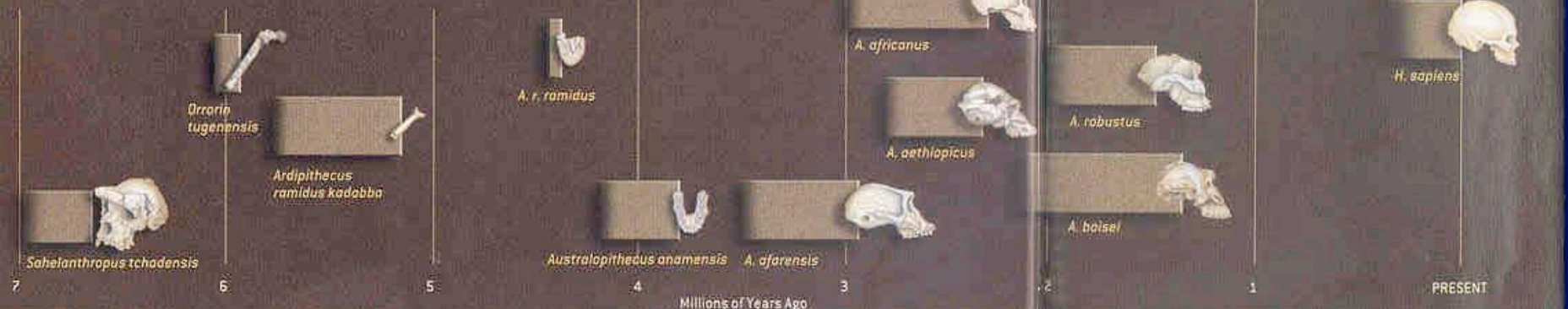
Scientific  
American  
Jan. 2003

# Various Family Trees

## Hominids in Time

FOSSIL RECORD OF HOMINIDS shows that multiple species existed alongside one another during the later stages of human evolution. Whether the same can be said for the first half of our family's existence is a matter of great debate among paleoanthropologists, however. Some believe that all the fossils from between seven million and three million years ago fit comfortably into the same evolutionary lineage. Others view these specimens not only as members of mostly different lineages but also as representatives of a tremendous early hominid diversity yet to be discovered. [Adherents to the latter scenario tend to parse the known hominid remains into more taxa than shown here.]

The branching diagrams (inset) illustrate two competing hypotheses of how the recently discovered *Sahelanthropus*, *Orrorin* and *Ardipithecus ramidus kadabba* are related to humans. In the tree on the left, all the new finds reside on the line leading to humans, with *Sahelanthropus* being the oldest known hominid. In the tree on the right, in contrast, only *Orrorin* is a human ancestor. *Ardipithecus* is a chimpanzee ancestor, and *Sahelanthropus* a gorilla forebear in this view.



Scientific  
American  
Jan. 2003

# Consequences of New Fossils

1. Even more clear that bipedal locomotion far preceded big brains
2. Bipedality not clearly connected to Savanna
3. Several of the oldest hominids are very close to Ape - Human split
4. Bipedality looks like key change that separated human and ape

# Ideas for Origin of Bipedality

X

1. Tool use, big brain feedback

??

2. Predator avoidance on savanna  
(adaptations for long-distance running  
unique to humans)

3. Food acquisition (carry food)

4. Reproductive Success (carry food & infants)  
("Bringing home the bacon")

# Humans and Chimpanzees: 1

- Recent data on genes of chimpanzees
  - Draft of chimp genome released in 2003
    - 99.4% the same as humans
      - For nonsynonymous sites (important)
    - Split from gorillas: 6-7 Myr ago
    - Human split from chimp: 5-6 Myr ago

## Humans and Chimpanzees: 2

- Paper by Wildman et al. (2003)
  - PNAS, 100, 7181
- Wildman et al.'s “modest proposal”
  - Family Hominidae includes all extant apes
  - Genus Homo includes chimps
  - “We humans appear as only slightly remodeled chimpanzee-like apes.”

## Humans and Chimpanzees: 3

- On the other hand...
- Cargill et al. (2003) Science, 302, 1960
- Studied what genes evolved fast
  - Chimps: fast changes in skeleton, skin
  - Humans: smell, hearing, speech, digestion
    - Adaptation to consuming more meat

# Humans and Chimpanzees: 4

- J. Zhang 2003 in Genetics, 165, 2063
  - Rapid evolution in ASPM gene
    - Mutations in this gene cause microcephaly
    - Brain about size of Australopithecus
    - So important for brain size
  - Rapid evolution in primates
  - Especially in line leading to humans
    - 15 changes since human-chimp split
    - May explain factor of 3 increase in size
    - Last change about 200,000 yr ago
    - Further developments are cultural (much faster)



# The Last Steps to Modern H. sapiens

## Origin of Modern H. Sapiens

Many anthropologists now believe that neanderthals were replaced by a new wave “out of Africa” ~ 100,000 yrs ago.

Alternative: Multiregional model

Separate groups of H. erectus leading to H. Sapiens (looks less likely)

Evidence: Genetic, linguistic, fossil

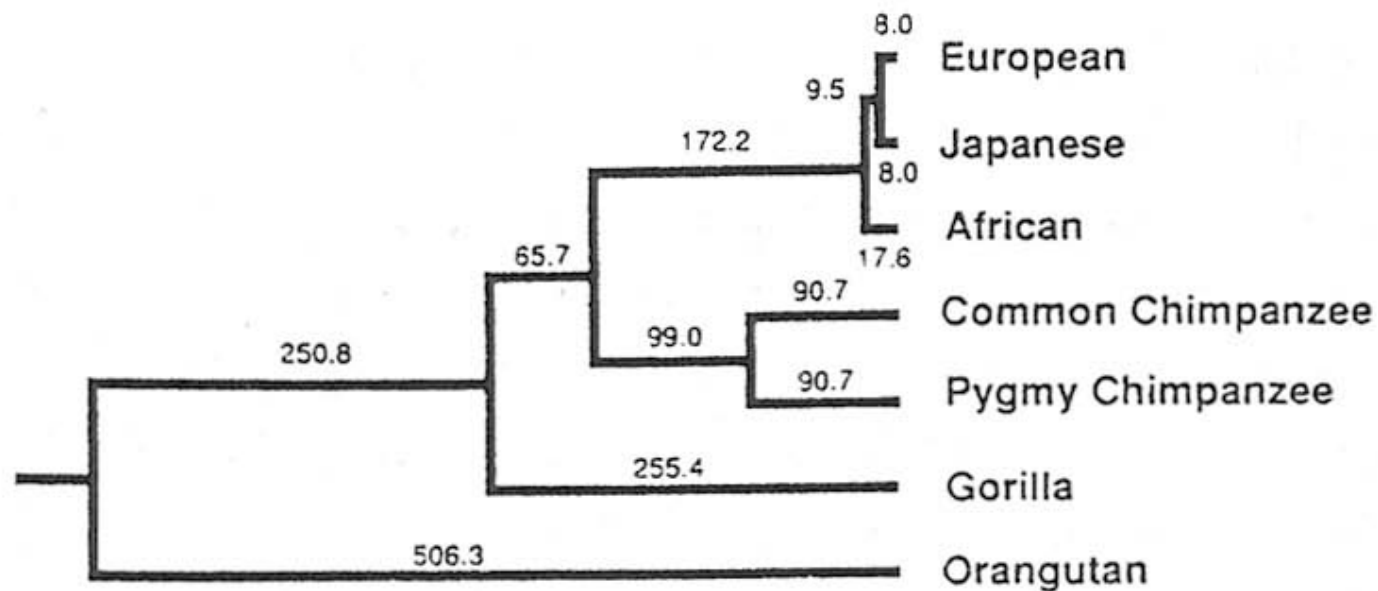
Genetic: humans are **very** homogeneous  
greatest diversity is in Africa

⇒ Evolved in Africa, population bottleneck  
a small group left Africa, spread over Earth

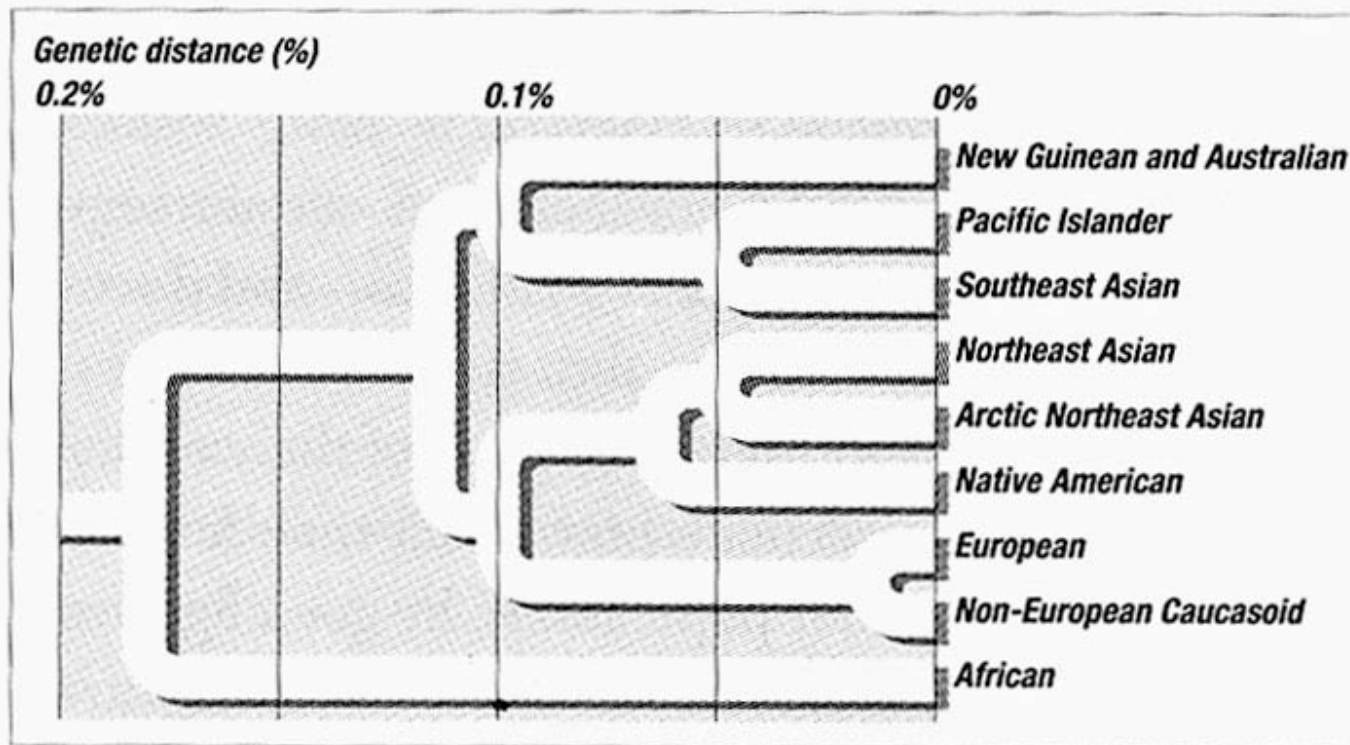
Linguistic: Good correlation of linguistic family  
tree with genetic one

Fossil: Oldest fossils of modern *H. sapiens* are  
found in Africa

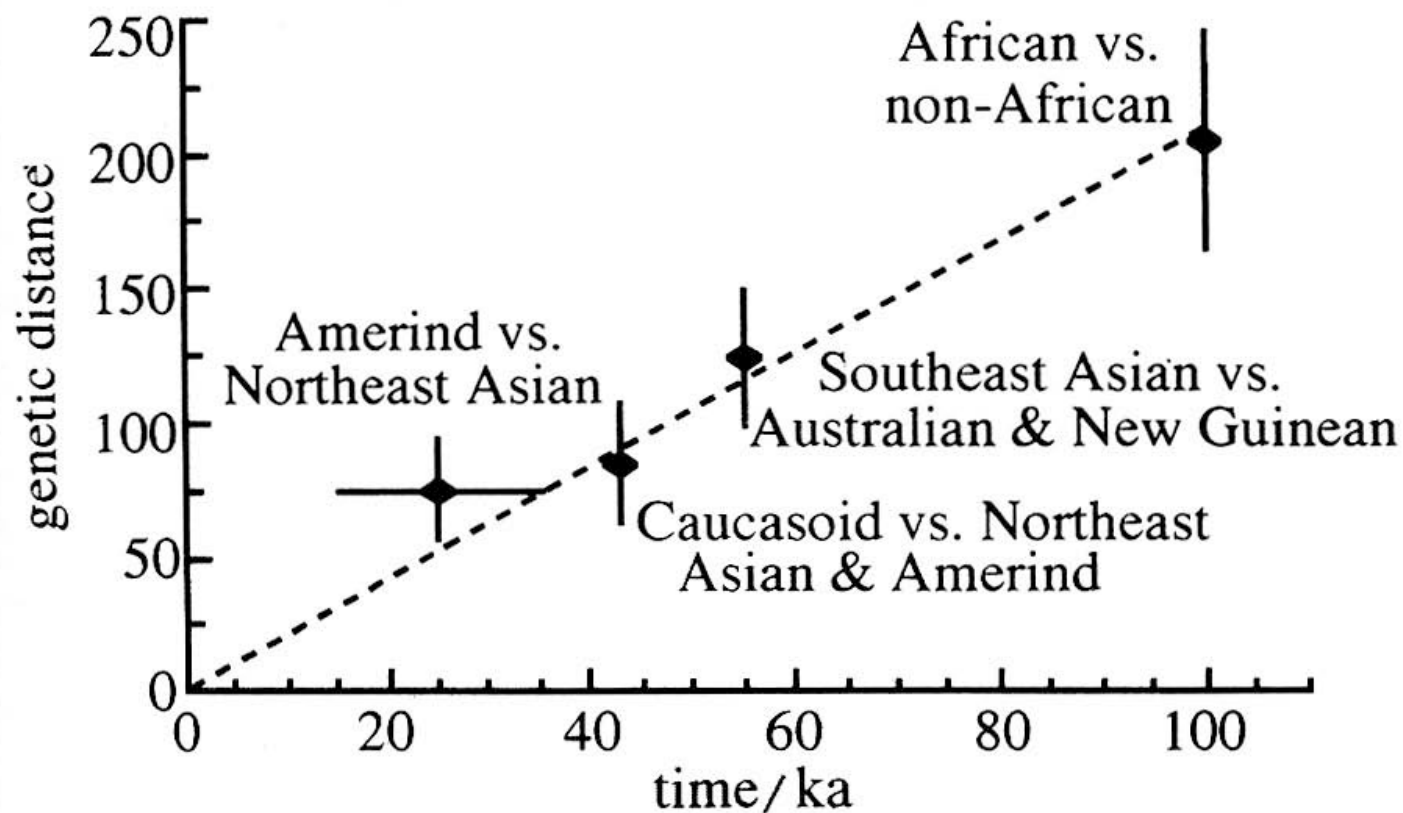
## From Stringer & McKie - *African Exodus*



- 38 Horai's mtDNA tree is based on complete sequences from both apes and humans (see pages 131–32). Note the shallow separation of the three human samples.



- 39 This tree of modern population relationships based on nuclear DNA products is from the work of Cavalli-Sforza and colleagues. The various African populations have been lumped into a single branch for simplicity.



- 40 Joanna Mountain and Cavalli-Sforza compared genetic distances between modern peoples with archeological and fossil evidence of their separations. They match well over a timescale of 100,000 years but would not fit much longer divergence times.

# Update on Genetic Analysis

March 2002

Genetic comparisons of more DNA sequences

(mitochondrial DNA, Y-chromosome, X Chromosome, ...)

female

male

female

Indicate 3 migrations out of Africa

1.7 Myr      H. erectus

~ 500,000    “neanderthal”

~ 100,000    Modern humans

But genes mixed (interbreeding)

Europeans may have some neanderthal  
genes (still controversial)

Asians may have some H. erectus genes

“Mostly Out - of - Africa”



# From J. Diamond: *Guns, Germs & Steel*

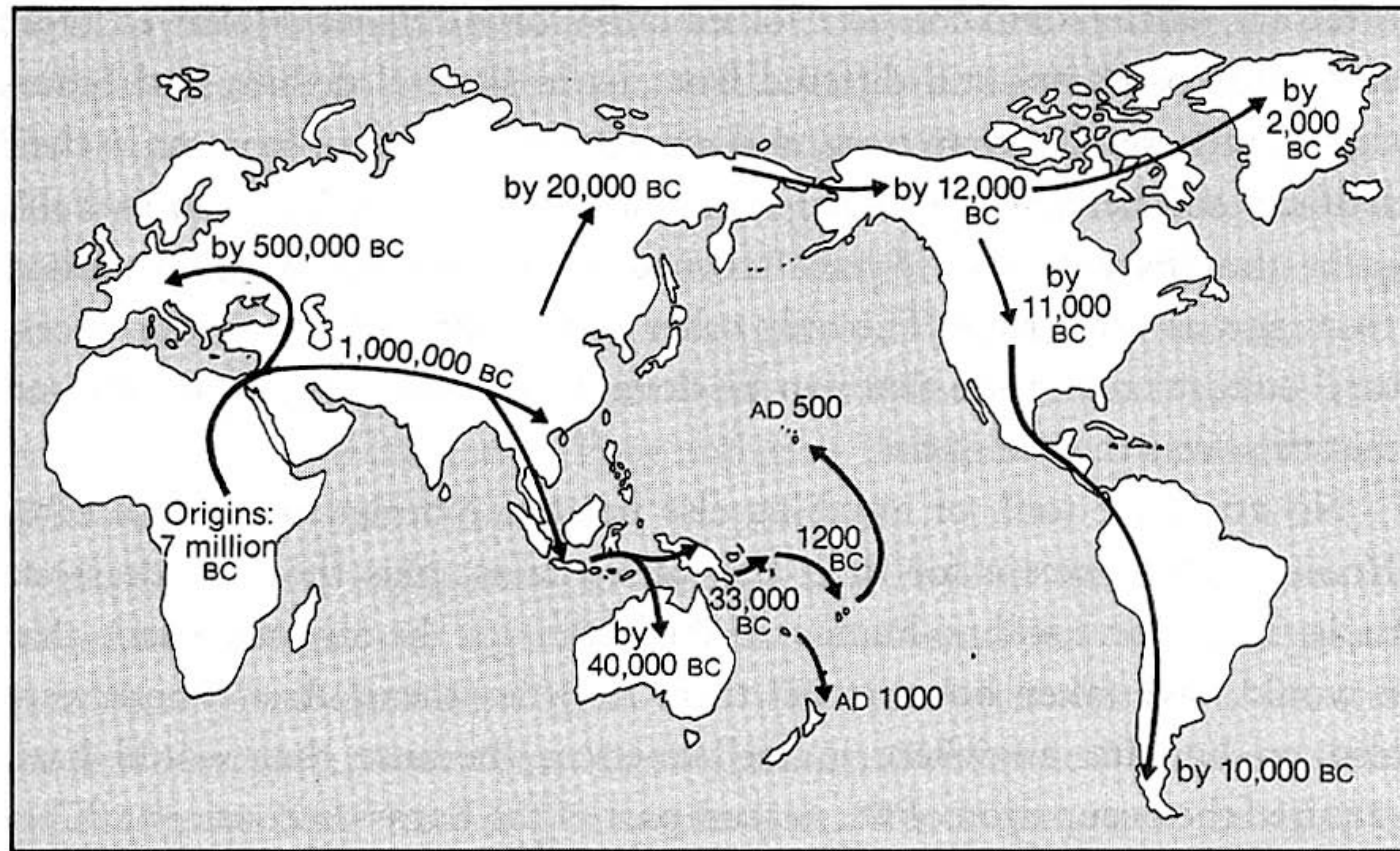
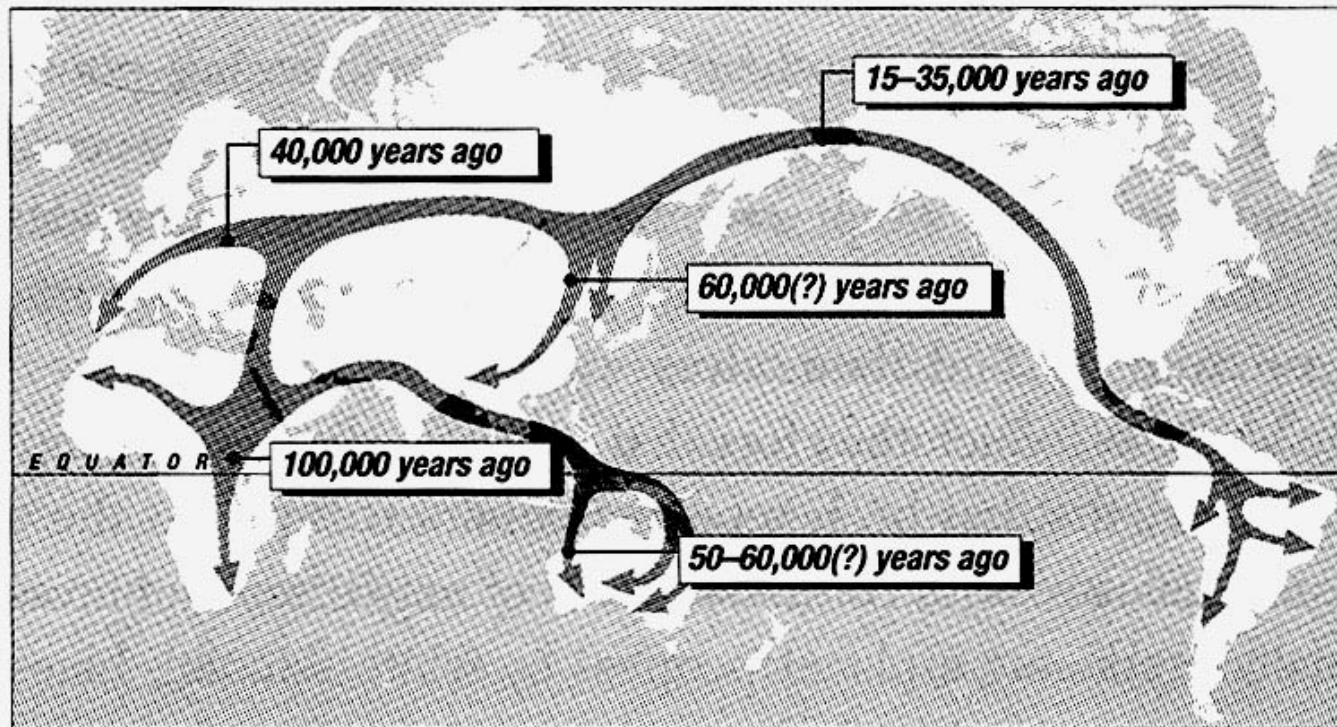


Figure 1.1. The spread of humans around the world.



# From Stringer & McKie - *African Exodus*



- 46 Genes and fossils have been used to reconstruct this map of the spread of *Homo sapiens* over the last 100,000 years.

# Questions

1. What **selected** for the increase in brain size over the last 6 Myr?
  - Adaptation to climate changes?
  - Cooperation and language (large-animal hunting)?
  - Intergroup conflict?
  
2. What **limited** the increase?
  - Size of birth canal (bipedalism **decreases** size)
  - Birth when less developed, so more care needed
  - Consequences of need for more care
    - pair bonding, more parental care available
    - slower development led to greater intelligence?

3. How intelligent are other species?  
(Chimpanzees, gorillas, ... dolphins, whales)

4. What features of *H. sapiens* would we expect in ETI?

Bilateral symmetry, bear young alive, bipedal, opposable thumb, ...

$$f_i = ?$$

# Contingency

Does evolution produce greater complexity?

What would happen if we replayed the tape with random changes?

Stephen J. Gould

vs.

Conway Morris

Contingency

vs.

convergent evolution

Extinction of  
Early Chordata



No intelligence

Other precursors



intelligence in  
other shapes

## Estimating $f_i$

### 1. Galactic habitable zone (GHZ)

Gonzales, Ward, Brownlee

Complex life requires more benign conditions  
more stars closer to center of galaxy (stars  
closer together)

Supernovae, X-rays, Gamma-rays  
could decrease  $f_i$

## 2. Timescales

Time to evolve human-level intelligence

$\sim 1/2$  lifetime of stars like Sun

$\Rightarrow$  rule out much more massive stars

(already done in  $n_e$ )

$\sim 1/2$  lifetime of galaxy so far

?  $\Rightarrow$  intelligent life is rare

Brandon Carter

? Statistics of one are suspect