

# 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

# Information as Measure of Intelligence

Evolution of intelligence  $\approx$  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

Pyrimidines

Adenine (A)

Cytosine (C)

Guanine (G)

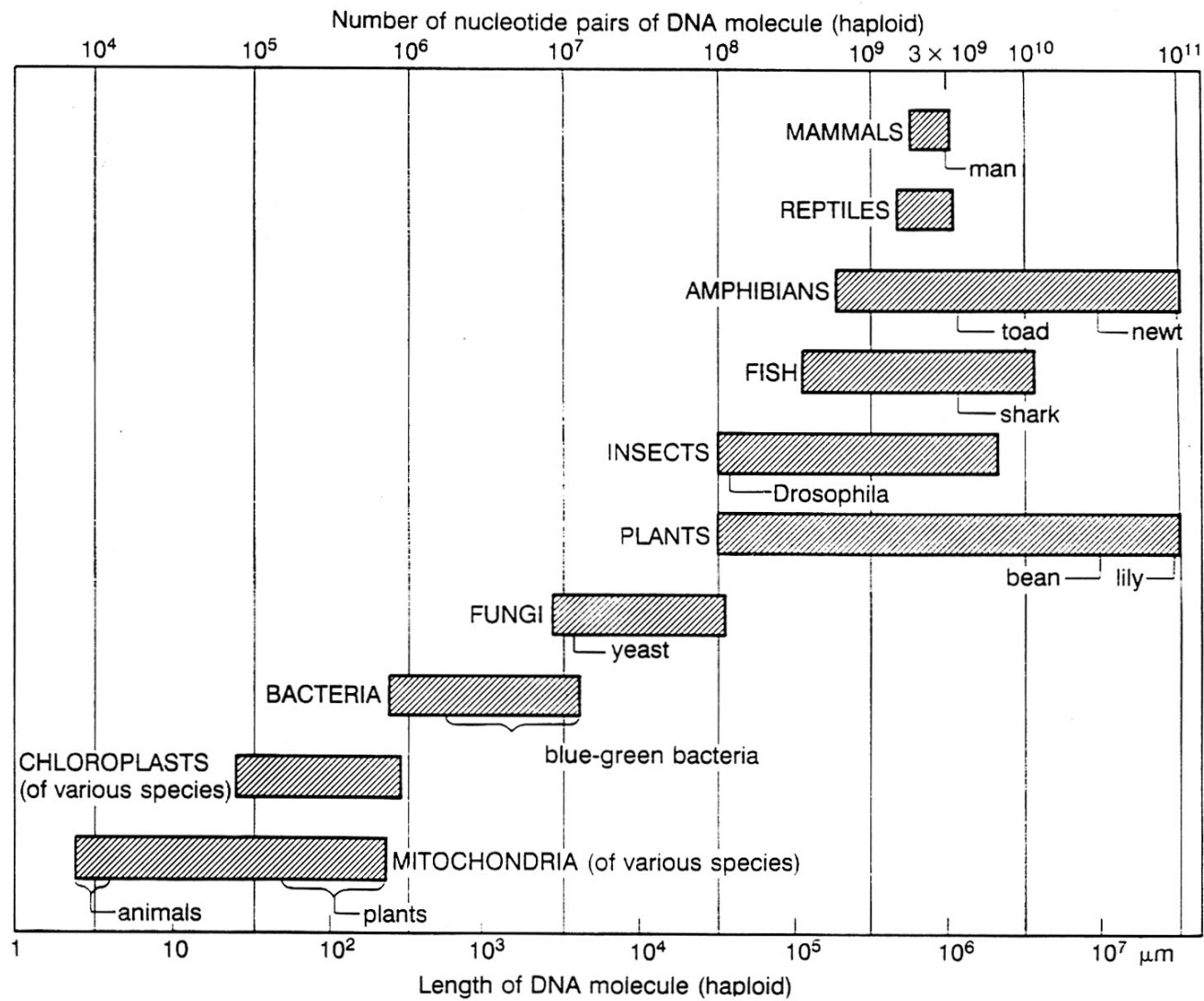
Thymine (T)

# 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*	$6 \times 10^9$		small library

\*~ 2% codes for proteins

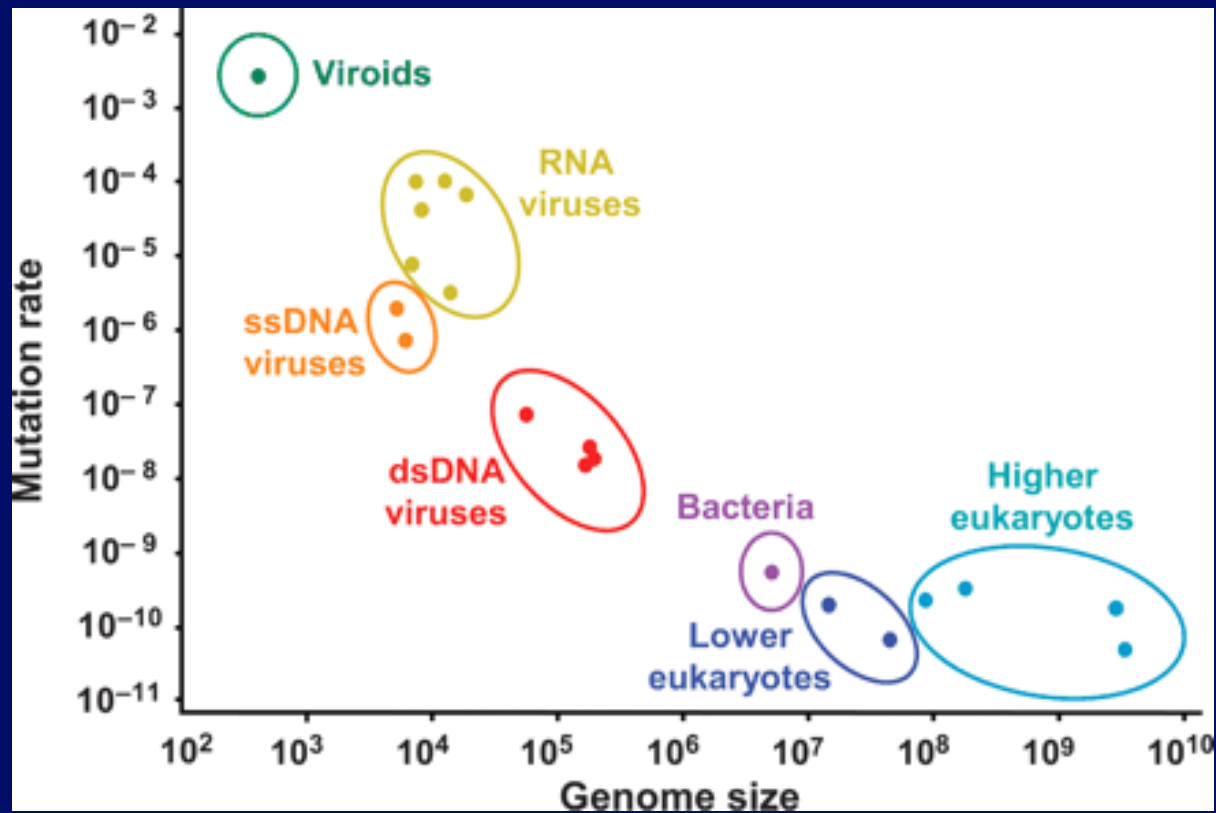
$\Rightarrow 1.2 \times 10^8$  bits



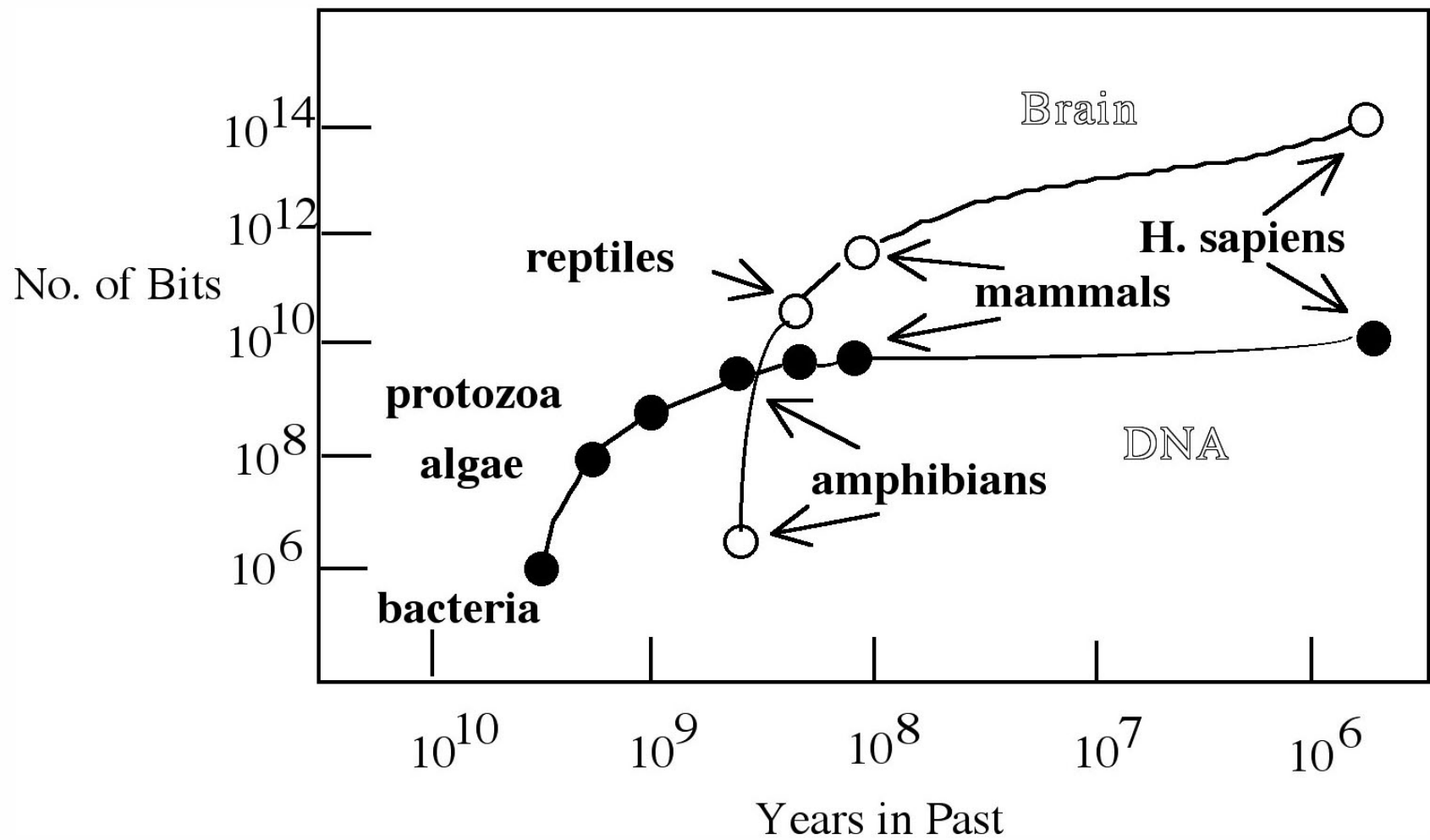
**Figure 7.18.** Length of DNA molecules. Note that the DNA of some plants and amphibians is longer than that of bacteria by a factor of  $10^4$  to  $10^5$ . The total length of human DNA is approximately  $10^6$   $\mu\text{m}$  or 1 m, which is equivalent to roughly  $3 \times 10^9$  nucleotide pairs 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

Information stored in DNA limited by fidelity of Replication. The bigger the genome, the smaller the mutation rate must be.



Gago et al. 2009, Science, 323, 1308



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

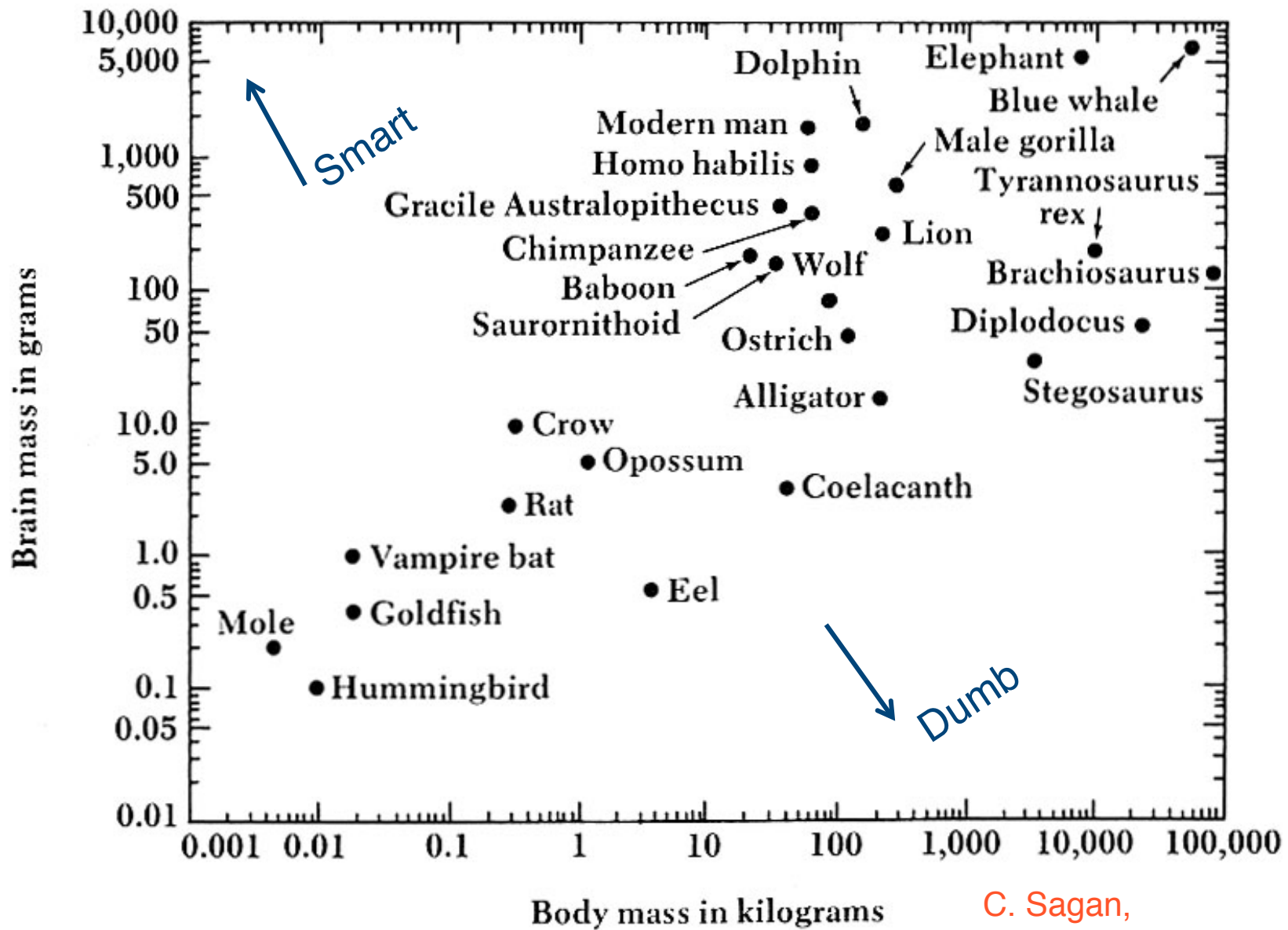
An **analog** computer  $\Rightarrow$  Hard to count

$\sim 10^{11}$  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

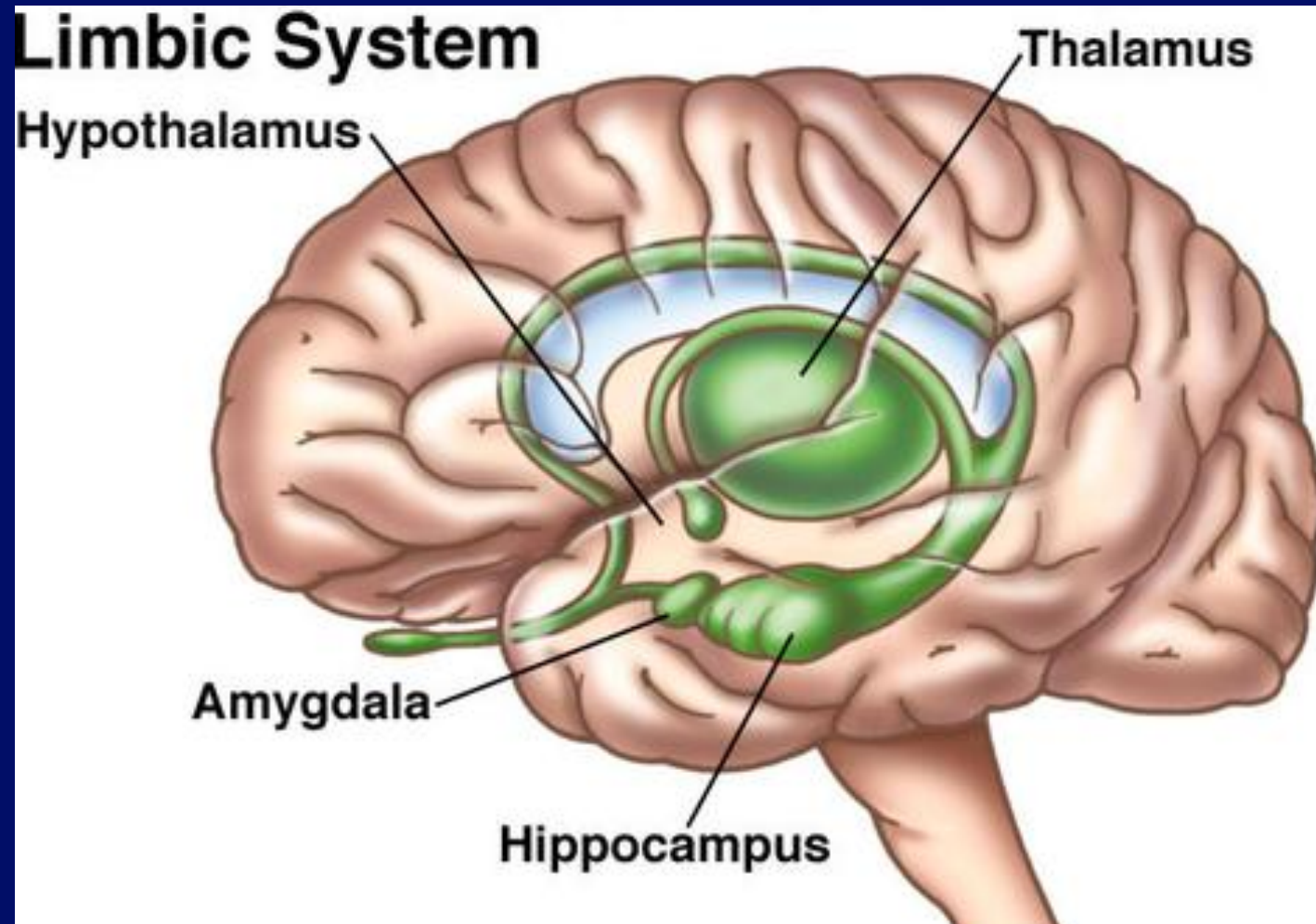
Many ways to divide brain

Layered brain:           reptilian brain  
                                  limbic system (mammals)  
                                  cortex

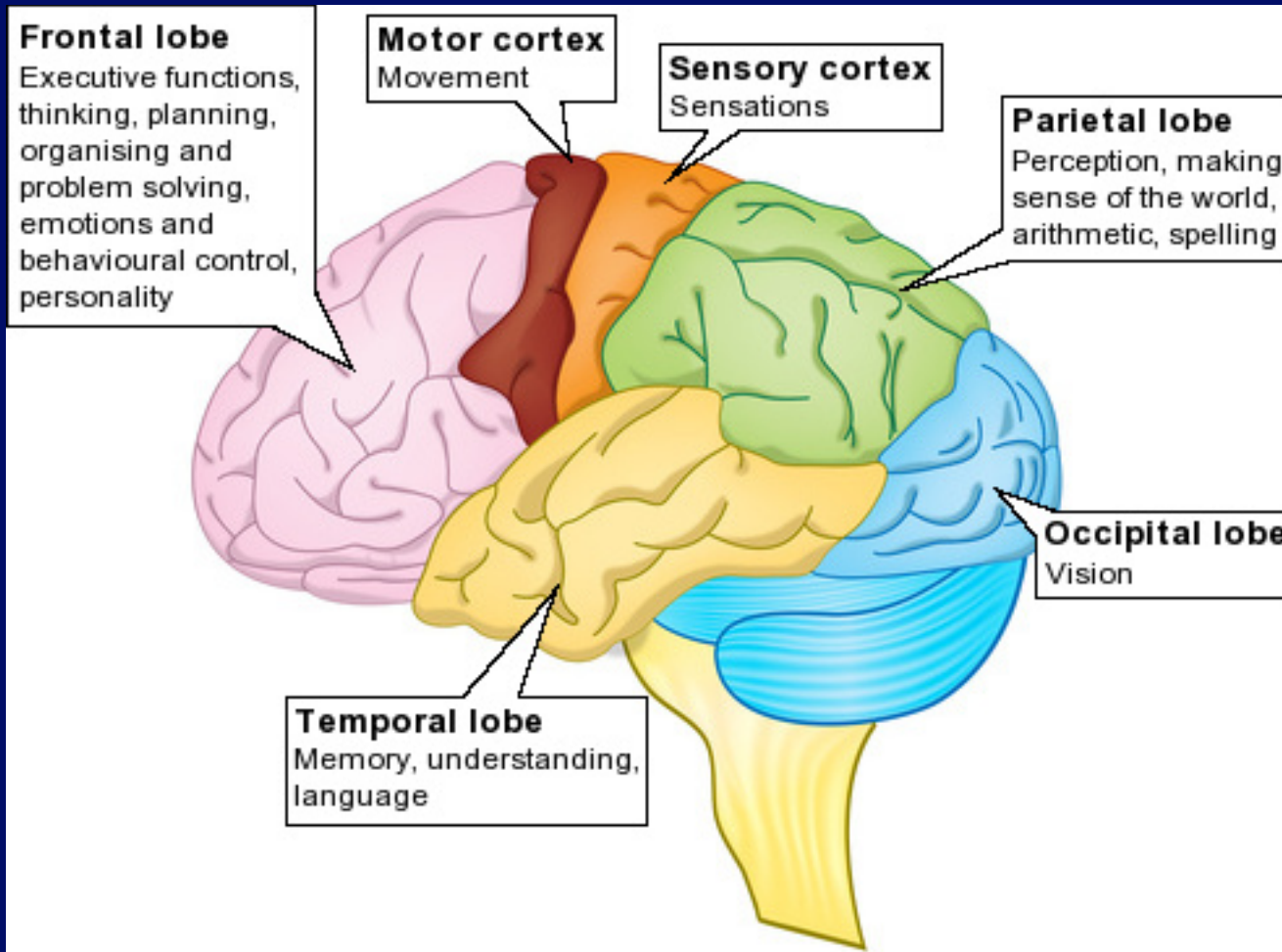
Brain size has increased (in some species) with time

⇒ Evolution favors higher intelligence (sometimes)

# Limbic System



# The Cortex





# Human Evolution

Phylum: chordata - vertebrates - bilateral symmetry

~ 500 Myr ago

Class: mammals - arose in Triassic period

~ 225 Myr ago

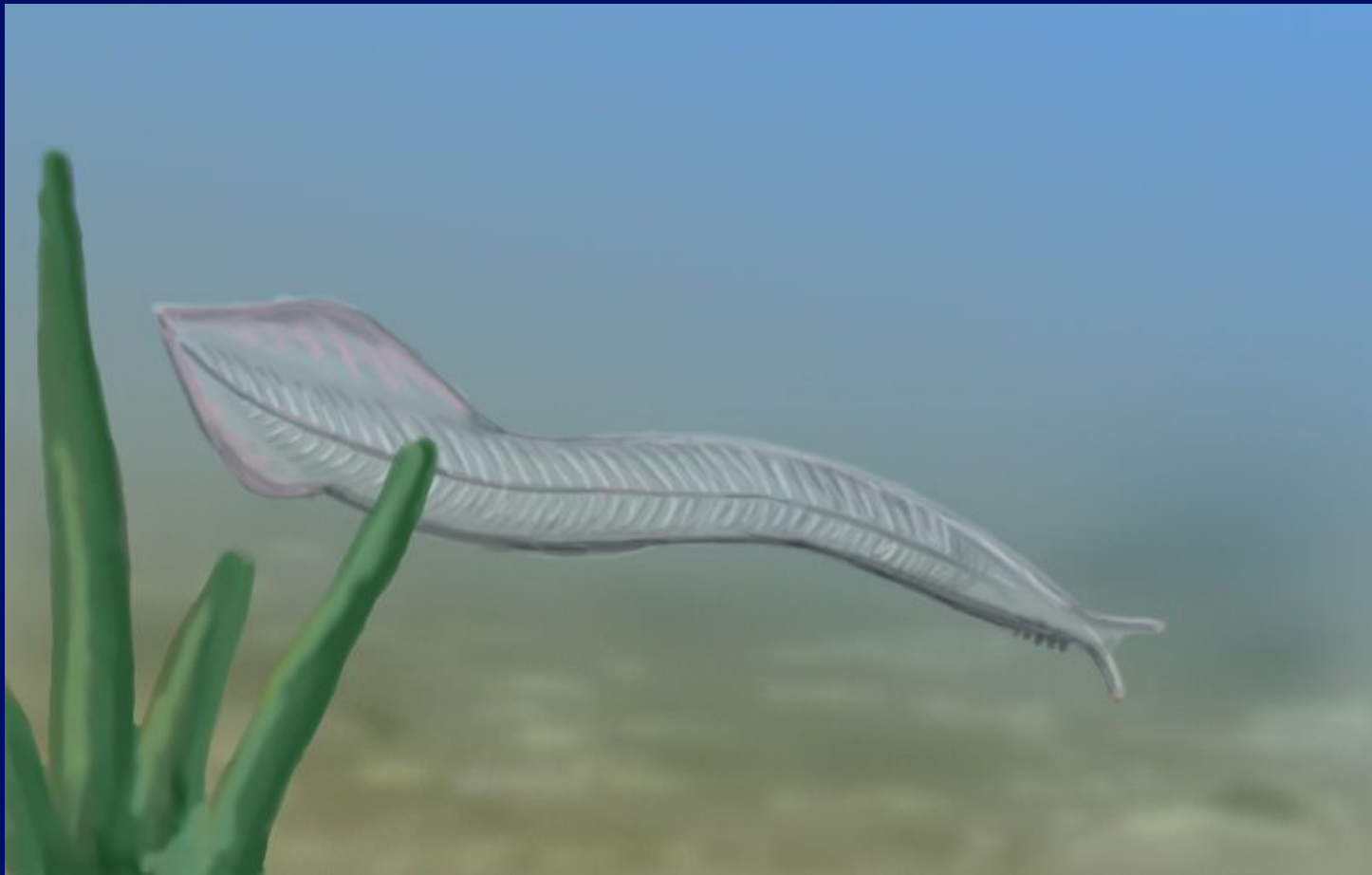
Proliferated and “radiated” at end of cretaceous

(66 Myr ago) after extinction of dinosaurs

Giant asteroid impact at that time

Order: primates - late cretaceous ~ 80 Myr ago

# Pikaia (from Burgess Shale)



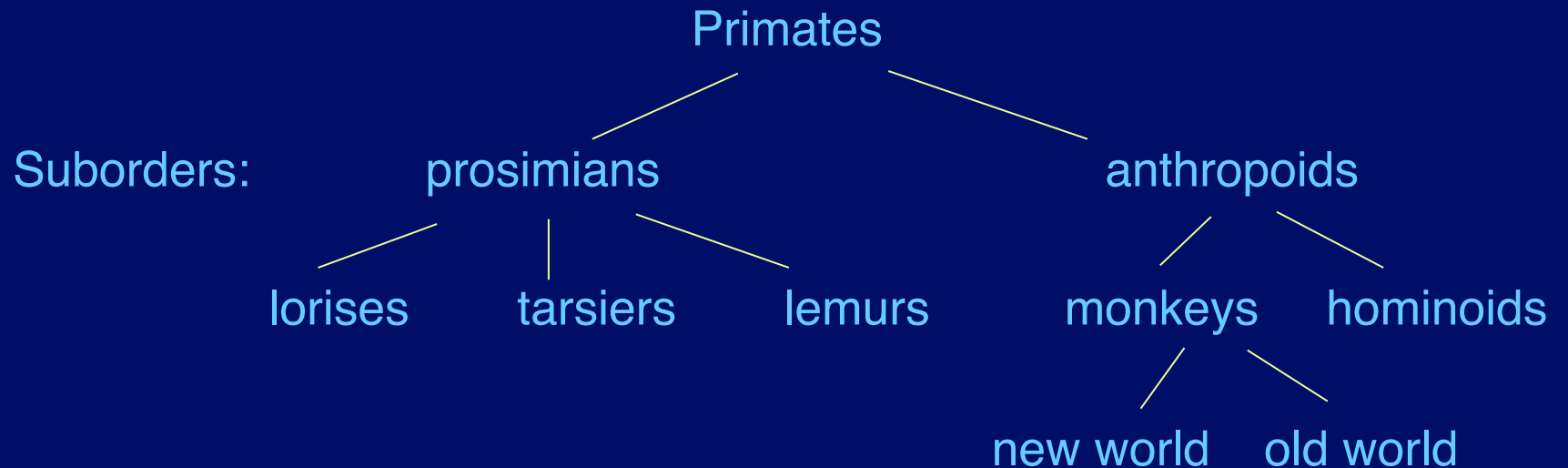


# Primate Characteristics

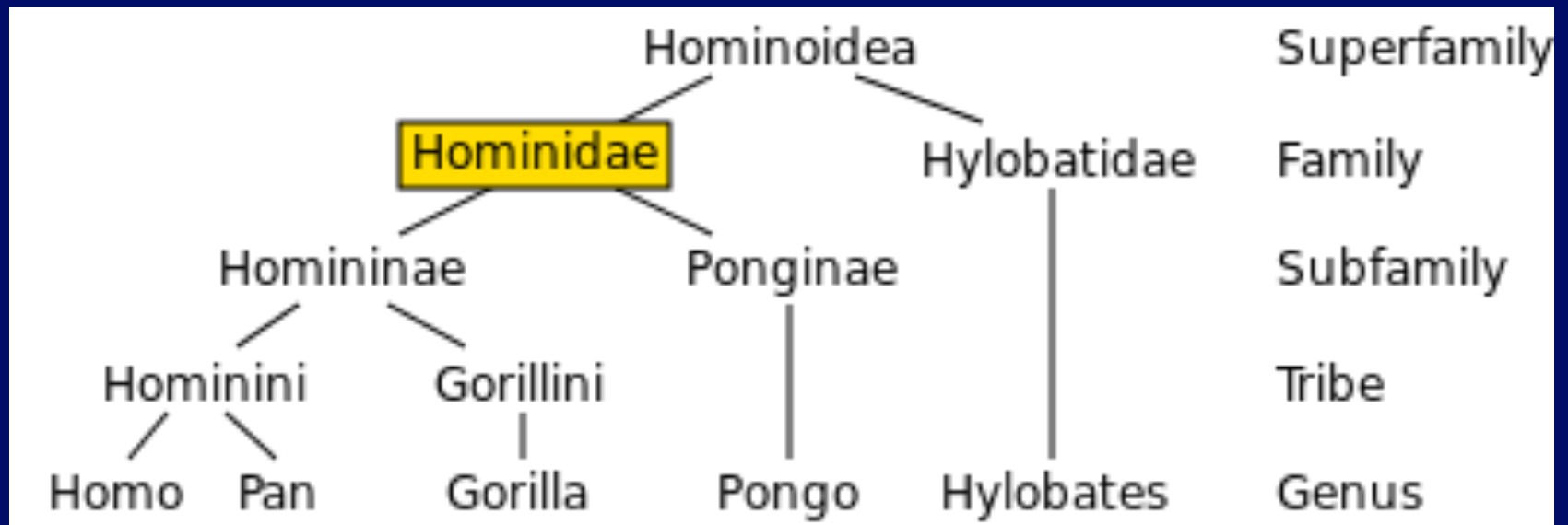
Few anatomical specializations

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:  
dates (in million years ago) are rough.

<b>Era</b>	<b>Period</b>	<b>Epoch</b>	<b>Time at beginning (Myr ago)</b>	<b>Events, Fossils of Note</b>	
Cenozoic	Quaternary	Recent	~12,000 yrs	Historical Records Homo sapiens Homo erectus	
		Pleistocene	2.5	2.8	Homo habilis
			4.2		Australopithecus
			5.5		Ardipithecus
		Pliocene	5.5		Sahelanthropus
					Gap
		Miocene		23	Ramapithecus Dryopithecine Apes
					Gap
				34	Aegyptopithecus
		Tertiary	Eocene		56
Paleocene	65			Tree Shrews - Primates Proliferation of Mammals Origin of Many Orders	
Mesozoic	Cretaceous				

# Early Primate Evolution

Adapting to life in trees

Claws → nails, grasp branches  
independent big toe, thumb

Nocturnal → diurnal

Smell → vision stereo vision  
(eyes in front)

Color vision

More complicated information processing

Tool use becomes possible

# Origin of Anthropoids

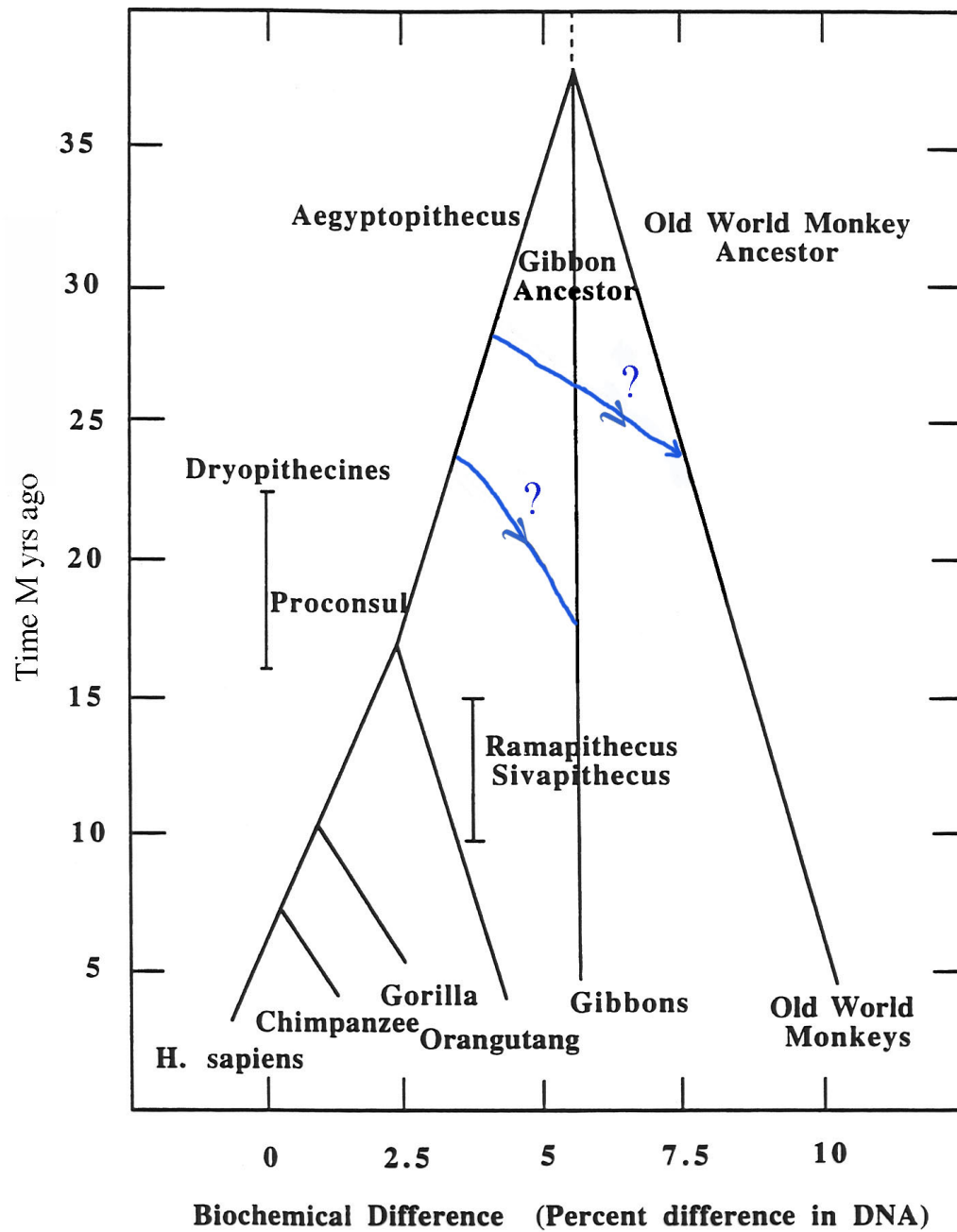
Eocene transition to oligocene ~ 37 Myr ago  
cooler, more grasslands

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 ~ 7 Myr

Genetic dating of chimp - hominid split 5-7 Myr

Many variations now known

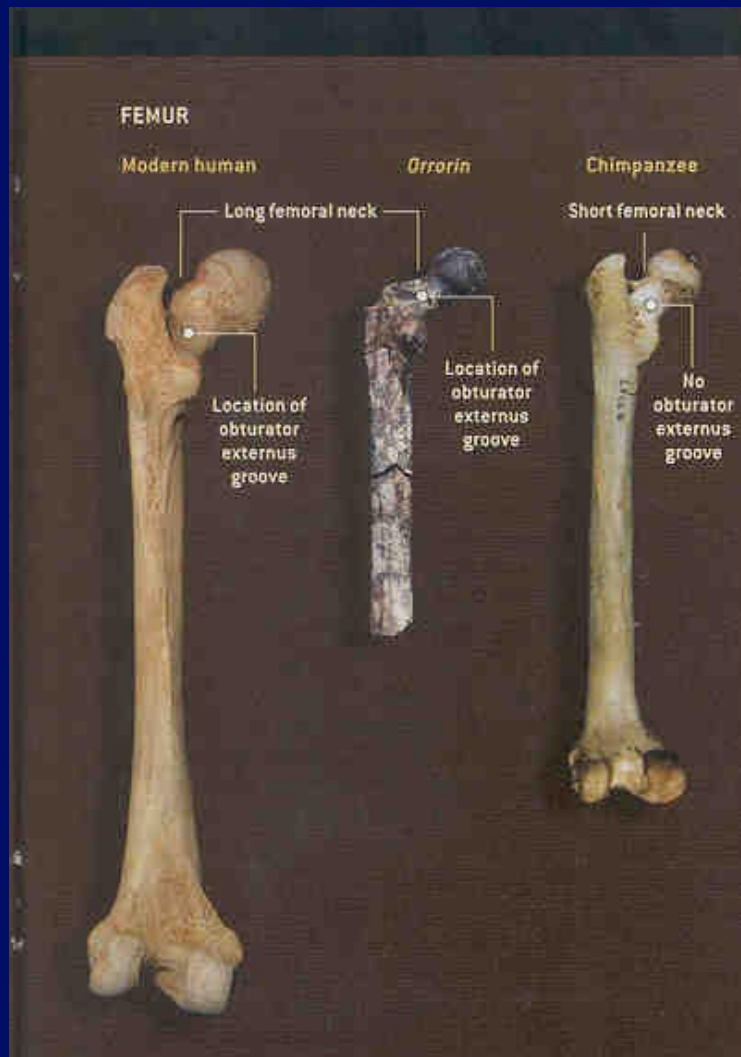
many species co-existed in Africa

Earlier species show mosaic of human-ape traits

Upright walking preceded brain growth, tool making

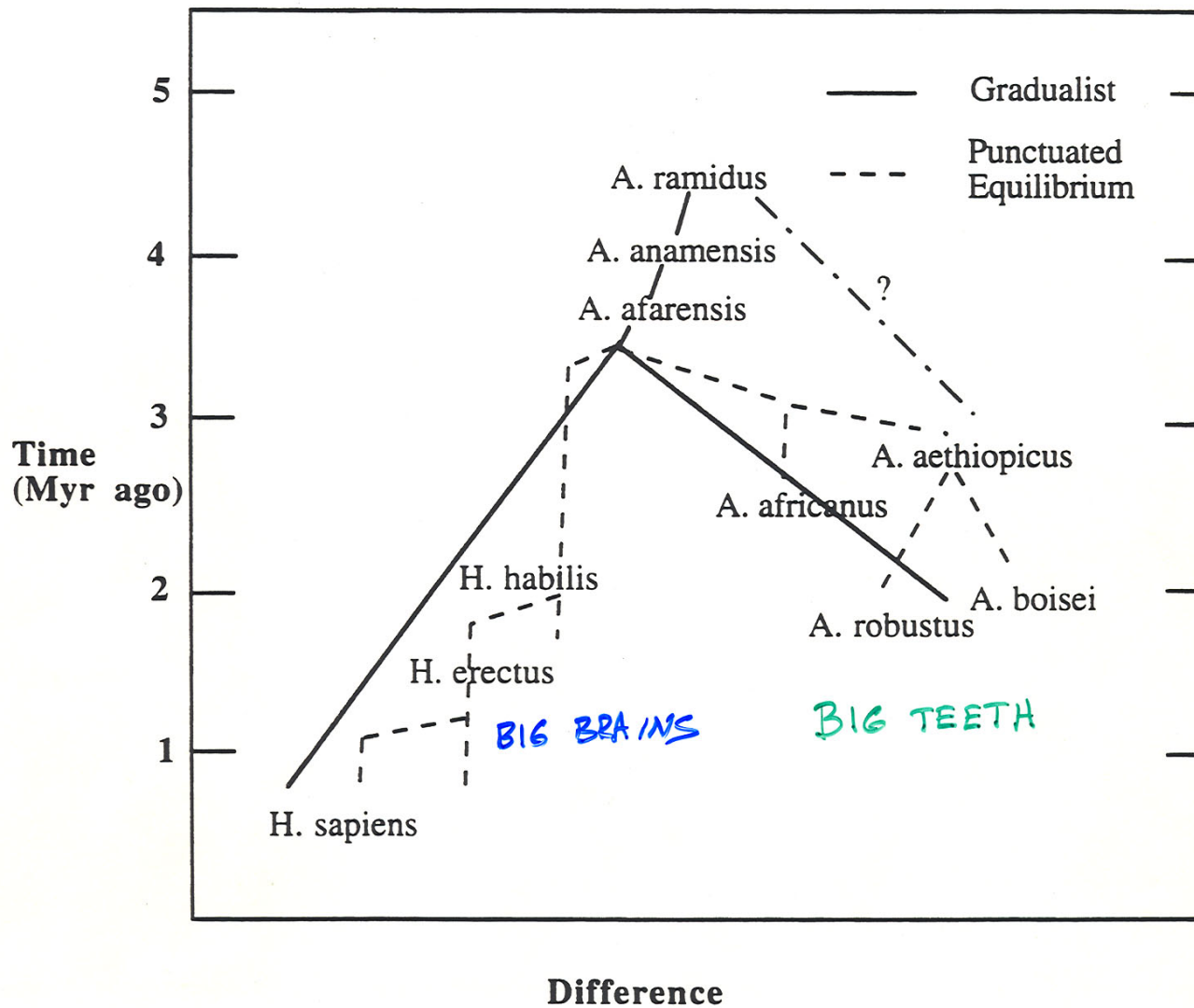


# Comparison of Femurs



Femur adapted to bipedality already by 6 Myr ago

Scientific  
American  
Jan. 2003



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.

## New Developments

- Oldest *H. habilis* fossils found recently: push origin back to 2.8 Myr ago.

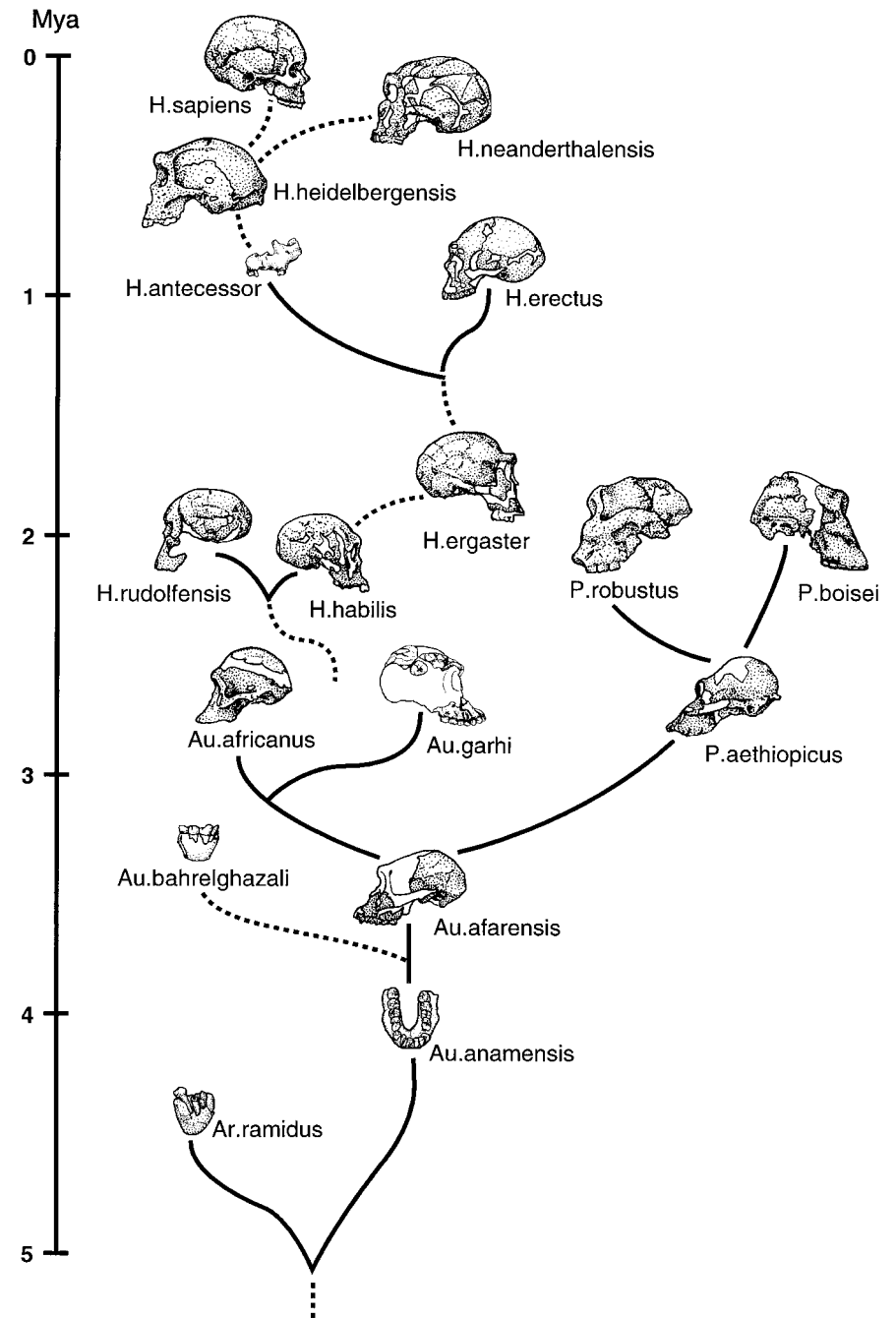


Science, 2015, vol 347, 1057

More Fossils, more complex picture with many possible species.

Main point: there was a major radiation, but only one species survived.

Were big brains highly selected?  
(Did we kill our “cousins”?)  
If so, argue for large  $f_i$   
Or was it chance that we survived?  
If so, argue for small  $f_i$





# Our Closest Living Relative

**Chimpanzees**



**H. Sapiens (Darwin)**



# Humans and Chimpanzees: 1

- Draft of chimp genome released in 2003
- Base substitutions: 1.23% difference
- Gene copies indicate bigger differences
  - Up to 6.4% in terms of duplications and losses
  - Some seem important in brain development.
- 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 *Australopithicus*
    - 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

## More Developments

- Several other genes involved in brain growth
    - Evidence for rapid evolution
    - Some may have evolved as recently as 6000 years ago (update on ASPM gene)
  - Differences in brain microstructure
    - Special (fast) neurons (VENS) in apes
    - Humans have many more
    - Some large whales also have VENS
- (brain story in Science 2007, 315, 1208)

# The Last Steps to Modern H. sapiens

## Origin of Modern H. Sapiens

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

Alternative: Multiregional model

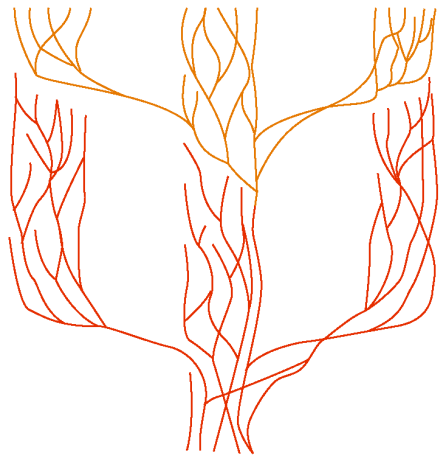
Separate groups of H. erectus leading to H. Sapiens (looks less likely)

Evidence: Genetic, linguistic, fossil

# Two Models

## Out of Africa

Europe Africa Asia



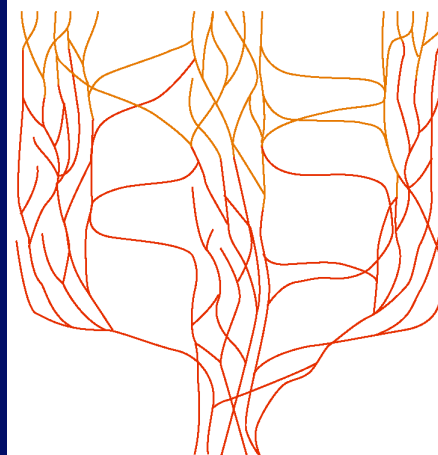
Anatomically modern *H. sapiens* evolves in Africa and then spreads to Europe and Asia.

*H. erectus* disperses from Africa.

Out of Africa model

## Multiregional

Europe Africa Asia



Anatomically modern *H. sapiens* genes arise in many populations.

*H. erectus* disperses from Africa.

Multiregional model

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

# Genetic Analysis: Out of Africa

March 2002

Genetic comparisons of more DNA sequences

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

female

male

female

Indicate 3 migrations out of Africa

1.7-1.9 Myr      H. erectus

~ 650,000    Archaic

~ 130,000    Modern humans

# Neanderthals and Us

- In 2009, analysis of DNA from Neanderthals
  - Science 13 February 2009:  
Vol. 323. no. 5916, pp. 866 - 871
    - 38,000 yr old fossils from cave in Croatia
    - Some evidence of inter-breeding with modern *H. sapiens* outside of Africa
    - 1-4% of modern human DNA may be from Neanderthals

# 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)

Recent evidence for weapon construction and use by Chimpanzees.

- 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

# Who is Right?

- Can't rewind the tape for macroevolution
- But remember the E. Coli 25 year experiment?
- Some samples were frozen every 75 days (500 generations)
- Could thaw out and rerun (bacteria survive freezing)
- 4 out of 72 developed citrate use
- Sometimes the rewind produces the same result!

# Estimating $f_i$

1. Galactic habitable zone (GHZ)  
Gonzales, Ward, Brownlee  
and Ward and Brownlee in *Rare Earth*

Complex life requires more benign conditions  
more stars closer to center of galaxy (stars  
closer together) **Supernovae, X-rays, Gamma-rays  
could extinct complex life**

If “animal” life has to avoid inner galaxy, this would  
decrease  $f_i$

## 2. Timescales

Time to evolve human-level intelligence

~ 1/2 lifetime of stars like Sun

⇒ rule out much more massive stars  
(already done in  $n_e$ )

~ 1/2 lifetime of galaxy so far

? ⇒ intelligent life is rare

Brandon Carter

? Statistics of one are suspect

# Summary

- Values for  $f_i$  can range from very small (e.g.,  $10^{-6}$ ) to 1
- Consider contingency vs. convergence
- Need for stable conditions
- The particular evolution that led to *H. sapiens*
- Consider other ways to get to intelligence
- Other species on Earth that may be very intelligent