Probability of “intelligence” for life on extrasolar planets

Basically, we would like to evaluate the factor “f_l” in the Drake equation: The probability that intelligence “like ours” will arise on an extrasolar planet where life arose sufficiently long ago. The considerations center on two questions having to do with convergent evolution:

1. **How convergent is “complexity”?**
2. **How convergent is “intelligence” (given a complex enough body, metabolism, etc.)?**

Let’s go along with book and just assume that one prerequisite for intelligence is a big brain (we return to this below). Then the basic line of development whose “convergence” we are interested in looks like:

→ **Complexity:** morphology, metabolism, perceptual apparatus, diversity of cell types, …	→ **Prerequisites for big brains:** bipedality, social interactions, use of fire, language, “theory of mind”, …	→ ***Intelligence*?**

The arrow on the far left corresponds to question (1) above, while the second two arrows refer to question (2).

What are the prerequisites for “intelligence” and when did they appear in primates? Before looking at the timing of prerequisites, here is a list of criteria for “intelligence” used in various areas of research:

1. Information processing capability (#neurons; #neural connections; brain size).
This is the only criterion that we can actually measure, in principal, and only for brain size (actually “encephalization quotient”), which we return to below. It is a shaky and crude assumption that intelligence can be measured by brain size, but it does give some results.

2. Ability to solve “complex problems” (in an efficient and adaptive way).
Who will decide what constitutes a complex problem? Is digging for termites by chimps *really* much less complicated than multiplication, or memorization tasks? (There is a famous story of an anthropologist who was unable to successfully learn how to dig for termites after six months of mentoring by a native adolescent chimp in Africa.)

3. Complexity of “mental models.”
The ability to model the world, including the organism’s own self.
Or: *Ability to form in the mind, conceptual thought.*

A favorite criterion is the **ability to attribute mental states to others**, today usually referred to as "mind reading". For many years it has been claimed that this was a uniquely human feature (how would we know about other creatures with no language?). There is some evidence that correlates "attribution of mental states" with I.Q. (for example) in school-age children, and it is regarded as part of a package of modeling of the world that is essential for the way humans employ their brains.

However there is also increasing evidence that chimpanzees and even monkeys perform this type of attribution of mental states.

A lot of people think this is an important criterion, but how can it be determined in animals without language have this ability?

4. ***Adaptive* cognitive behavior.**

The idea is that there are cognitive behaviors that allow (for example)

- enhanced protection of offspring,
- more efficient foraging and scavenging,
- ability to manipulate others ("Machiavellian intelligence"),
- or even superior grooming ability! (Because it may enhance reproductive success.)

Despite the hand-wavey nature of this category, it is the easiest to write books about, and there are a large number of papers and books trying to trace intelligence in this way.

An interesting example: Perhaps an early trigger in the development of intelligence was the ability to use **chemical fuels, i.e. fire. Earliest evidence for this is ~ 1.5 Myr ago, in Homo Erectus (see notes below)**

→ Consider what this says about oxygen on planets with intelligent life—there were no natural fires on Earth until long after the great oxidation event, because fire requires something like 10% concentration of oxygen in the atmosphere. Another reason to attempt direct detection of ozone bands in the spectra of extrasolar planets!

5. **Anything a culture says it is (radical cultural relativism).** This is a terrifying or disgusting idea to many people, scientists and public alike, because it suggests that we literally don't know what we are talking about, that others could be as "intelligent" as we are, that the entire idea of "intelligence" was largely a construction required in order to have regimented and unified "educational systems,"… Yet it is also in some ways the easiest case to make—there are many surprising examples from the field of comparative cultural psychology, which we will have to skip.

So we see that the question of "what is intelligence" is really at the root of our problem. Nevertheless, since, at least for SETI searches, we really are only interested in detecting signals we can understand, implying intelligence "like ours" in some sense, people in the SETI community to not worry much about the fact that we don't know what intelligence really is.

It is a useful exercise to ask yourself how you would explain "intelligence" as it applies to present-day humans, or animals, or infants, or all creatures during the history of life on Earth. How much of your attempt is biased by your own perception of yourself in relation to others? How much is a product of what you have been "taught" in schools?

Complexity and Chance Mutations

I give only a couple of the major questions that we would like to answer, but can't.

● **Did complex animals arise only because of a chance mutation in plants?**

An exceptionally important development that doesn't get much "press" occurred around the end of the Cenozoic era 65 Myr ago, and is a useful example of contingency. Plants today require molecular nitrogen for nutrition, but until this time plants could not use nitrogen directly—the triple bond linking the two N atoms is very stable. However mutations in one group of plants allowed them to use atmospheric molecular nitrogen directly, by a symbiosis with a few species of bacteria who learned "nitrogen fixation" much earlier. The way in which plants obtain fixed nitrogen from the bacteria, and bacteria obtain products of photosynthesis, high-energy compounds, is an example of simultaneous *symbiosis* and *mutualism*.
The nitrogen cycle is essential for life on Earth today: nitrogen-containing compounds constitute 5–30 percent of a plant's total dry weight. The nitrogen content of animals is even higher, and all the nitrogen in the animal world arrives there by way of the plant kingdom.
→ **One could question whether there could be complex animals without nitrogen-fixing plants. Yet this event was due to mutations in two genes in one group of plants.**

We previously saw evidence for a mutation in a single gene that was apparently responsible for the development of the modern eyeball. Evidence was discussed in class that the increase in brain size that many think was crucial for our kind of intelligence may be due to similarly chance mutations in a few genes. These kinds of events are strong arguments for contingency, or present-day life being a product of an endless string of chance events, from a rare mutation to a 10 kilometer bolide impact.

● **Doesn't evolution have a *direction*, and isn't that direction is complexity?** Shouldn't we expect "complexity" to develop in life forms anywhere, whatever other differences there are?

This is probably the most important question about life, besides its origin, that we can ask. And the answer appears obvious: There is no doubt that if we start with the earliest fossils, we see a progressive change that consists of the appearance of more diverse body parts, that are functional and specialized. It is not that long after the "Cambrian explosion" that we see flying creatures with internal, delicately connected, organs, that regulate a massively hierarchical physiology and an amazing variety of differentiated cell types that carry out more functions than we could possibly catalogue. Yet of all the surprises accompanying the advent of genome sequencing for many organisms, including the fact that the genome-level processes are much more complex than we had ever guessed, is an apparent repudiation of this idea that evolution has a direction, and that direction is complexity.

→ The most important point about complexity as a direction is that, starting with the simplest creatures, there is really only one way to go in terms of complexity, producing a gradual "diffusion" away from the "wall" of the simplest cells and creatures that could exist, even though there is no "natural" tendency for evolution to create complexity.

A pictorial representation of this process is shown below.

Many favor passive evolution of complexity (left)—no intrinsic direction to natural selection. Only maximum increases. Most organisms are prokaryotes, which have not increased in complexity at all.

T. Miconi Evolution and Complexity: The Double-Edged Sword

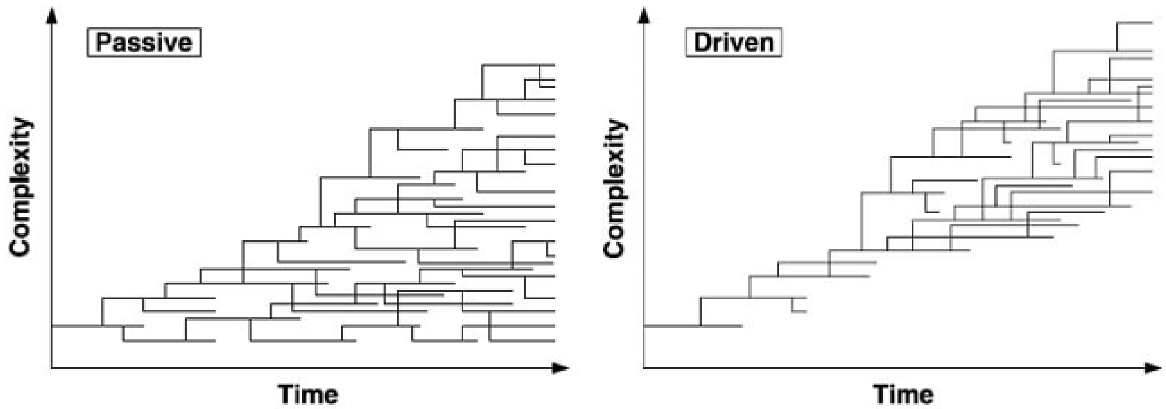


Figure 1. Passive and driven trends. In both of these graphs, the maximum and the average follow a trend of sustained increase through time. In the left-hand graph, these trends are *passive*: The branching process is not biased towards higher or lower values. A trend in the maximum emerges mechanically by envelope expansion. A trend in the average also emerges, because the process is constrained by a hard lower bound that cannot be crossed. Both trends, resulting from a globally unbiased process, are passive. In the right-hand graph, however, the trends of increase in the average and the maximum are *driven*: The underlying branching process is clearly biased towards higher values.

Some evidence:
Lack of correlation of genome length with other indicators of complexity. (see below)

Study showing dominant evolutionary mechanism in bacteria has been gene *loss*, *not* either gene duplication or horizontal transfer of genetic material (Wolf and Koonin 2008)

For SETI, you may be able to see that all we care about ***is*** maximum complexity, not the average or most common level of complexity. So both the passive and active models answer "yes" to the question of whether the maximum complexity increases with time. The missing piece is that they don't tell us the ***rate*** of increase.

→If maximum complexity always increases, but you only get to multicellularity or even vertebrates in a trillion years, that is as good as not having the complexity we need for SETI intelligence. **So it is the *rate* of development of intelligence that is the crucial missing piece.**

If complexity increases, it should make an appearance as larger genomes (more base pairs in DNA) for more complex organisms. This makes sense, because genes are supposed to code for traits, and a complex trait should require a large chunk of genome. Right? Not so quick…

Complexity and Genomes

[*This material is summarized in the two-page handout you received in class, or downloaded from the course web site.*]

We have complete genome sequences for 100s of organisms. We expect to find clues about the evolution of complexity reflected in complexity of genomes.

Compare human genome with pygmy chimps (pan paniscus).
This is a popular but misleading argument:

- About 98% of DNA in common with this species. (Similar results from all molecular clocks: mitochondrial DNA, protein amino acid sequences, DNA hybridization, and base sequences.)

Many other behavioral similarities between humans and pygmy chimps: e.g. Food sharing; strong social bonds; sexual similarities, …

- So if intelligence is unique to humans and is coded in the genome, it must be concentrated in *less* than 2% of genetic material. (*Less* because much of the DNA sequence does not code for function—introns, etc.)

- Could so much difference come from so little genetic material?

Answer: It is not as small as it sounds: Human and chimp genomes are nearly 10^8 (100 billion) *coding* base pairs in length, so 1 percent of that is still a **million base pairs**, which is a *lot* of genome. *So this argument is not valid.*

And the similarity with other animals is not restricted to chimps or even primates. For example, Koop and Hood (1994) found that, for a region of DNA ~ 100 thousand base pairs long that codes for T cell receptors, *the sequence similarity between mouse and human was 71%*. The fact that much of this was in noncoding sequences was part of the evidence that these sequences are not "junk DNA."

→These cases demonstrate that we share a common ancestor with a lot of species, not that we have nearly the same genome.

Nevertheless, if human-like intelligence, or other traits to which it may be connected, is unique to humans, built into our neural circuitry, we expect to find a section of our DNA that codes for this trait.

→If this is a long section of the genome, then it might makes sense that intelligence is a complex, possibly adaptive trait, requiring many genes to carry out its functions.

→ But if we found that intelligence was carried by a single mutation in a gene, or even a few, that would suggest that, whatever the factors that led to our "intelligence," they happened by chance, and might be unlikely to ever happen again.

- Some traits *are* specified by a single protein and gene. e.g.

hemoglobin (oxygen-carrying protein);
Tay Sachs disease (fatal)--carried by 1 enzyme and 1 gene;
Sickle-cell anemia--change in just one of hemoglobin's 287 amino acids, due to change in just 1 of 3 nucleotides that specify that amino acid.

The last example is especially interesting because although it is a deleterious mutation in present-day Western populations, it was once a beneficial gene that conferred protection against malaria. So by its present context, it would not be regarded as convergent, but it might be (because it seems adaptive) in the context of malaria. But these would both probably be incorrect. Whatever the mutation is, it did not develop for some *purpose*—evolution cannot "see the future."

Similar large changes from small DNA differences are well known in other species.

- But other traits are probably affected by *many* genes (no one knows), as well as external factors. e.g. height as an adult--determined by many genes as well as nutrition as child. Complex behaviors? e.g. aggression, language, homosexuality, ...intelligence?

So let's look at size (length) of genome, to see if we see correlation of complexity with genome size.

Genome length (size) as measure of complexity?

Beginning in 1995, complete genome sequences for 100s of species from bacteria to humans have been derived, and we can meaningfully speak of genome size. The very striking result is that

→ **genome size is not correlated with some other indicators of complexity**, such as the number of cell types used in a given species.

<u>Examples:</u>

Bacteria have smaller genomes than mammals, as expected, from about 0.1 million to 10 million base pairs (bp); compare with graph above.

Eukaryotes: the range in genome length is enormous.

Fish may have an average genome length of only 0.1 billion as shown in the figure, but the Marbled lungfish: 130 billion bp in length, dwarfing the 3 billion bp human genome.

The plant Fritillaria assyrica has a genome also 30 times the human genome.

The largest known genome is that of the Amoeba dubia, at 670 bp.

Many single-celled protists have genomes larger than the human genome.

This should convince us that, if humans are complex, it is *not* reflected in the *length* of the genome, i.e. how many base pairs it contains.

How about number of genes? (coding sections of DNA, "open reading frames")

Humans: About 20,000 genes.

Highest known number of genes is around 60,000 for the protozoan that causes trichomoniasis.

The diatom Thallassiosira pseudonana is extremely simple compared to humans, yet has nearly half as many genes, as does the mosquito.

Again, human complexity (or mosquito simplicity) is not reflected in number of genes.

A likely explanation for this paradox: most of the potential for complexity is actually contained in just the mobile genetic elements, the "transposons," that were at one time called "junk DNA" because they didn't code for anything, and seemed to be just "dead" genes.

→ It is now appearing that complexity *is* reflected in the genome, but not in as simple a measure as its size, but rather in the complexity of the genome itself—transposable elements, gene duplications, polyploidy, … **All mobile genetic elements: *"the mobilome"***

➙ The important implication for SETI is that taking "brain size" as a measure of complexity could be as dangerous as using genome size.

Hominid Evolution

Can we find similar examples of change among human ancestors that will give us some idea of how and when intelligence arose in humans?

We are most interested in developments from about 6-8 Myr ago, the time of first evidence for bipedal hominids, to about 0.3-0.5 Myr ago, the generally agreed upon time when “modern humans” were in place—modern because of features like boat travel, jewelry, art, weaponry, as well as anatomical likeness that has not changed much to the present. (However note that there was at least one, and possibly two, other *homo* subspecies around during this period.)

During this time the prosimians, monkeys, and great apes continued to thrive, but some time around this period we see fossil bones and especially skulls that appear as a distinct branching from this lineage, leading to the hominids.

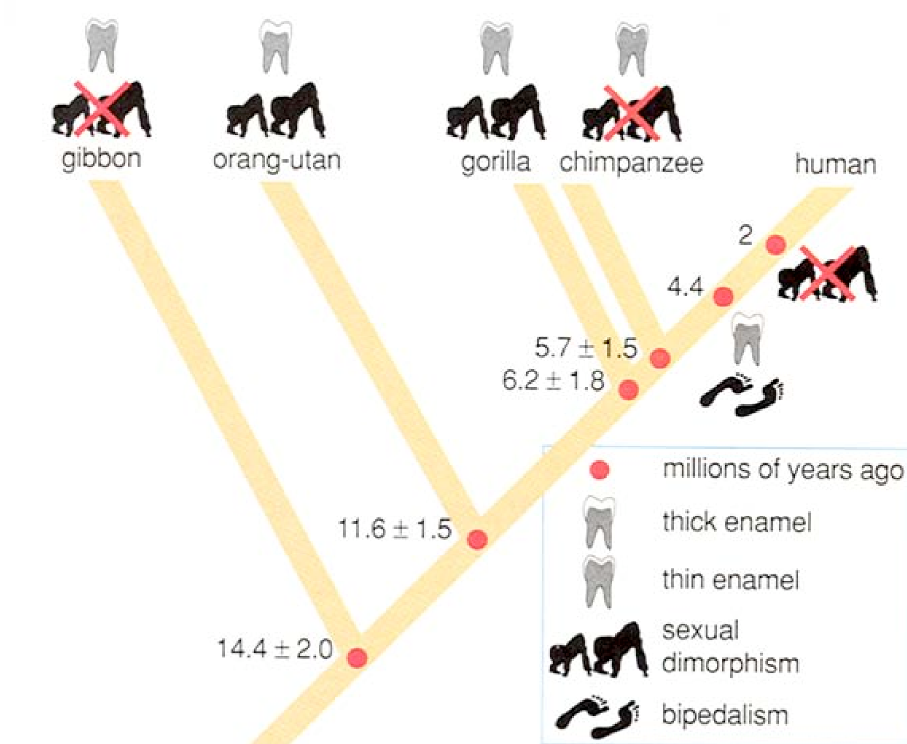
Also during this period Earth had gone through several cold/dry climate cycles, with repeated glaciations. In fact during the Quaternary (1.8 Myr to present), there were four major and about 20 minor “ice ages, during which the ranges of animals and plants shifted toward the equator. The last of these retreated only 15,000 years ago. Interestingly, relatively few species became extinct during these climate fluctuations.

With these considerations in mind, we turn next to evolution of hominids and humans.

Some of the main features of hominid evolution that have been pieced together over many years are summarized in some illustrations below.

One feature of interest is our relation to other primates. The first illustration shows the **branching of the great apes and then hominids from the earlier line of primates around 5-7 Myr ago,** with the gibbons and orangutans representing a still earlier branch, leading back to the tree-living **prosimians** (discussed in text but not shown in illustration); **the prosimians arose about 40 Million years ago.** ***Your textbook attributes many prerequisites for intelligence to the tree-living attributes of the prosimians.***

The author of the chart is arguing that if you compare certain important physiological traits that were or weren't present in different parts of the primate lineage, you might notice that the **loss of sexual dimorphism**, meaning a reduction in the huge difference in size between males and females, might be used as a major factor that led to modern human behavior and intelligence.



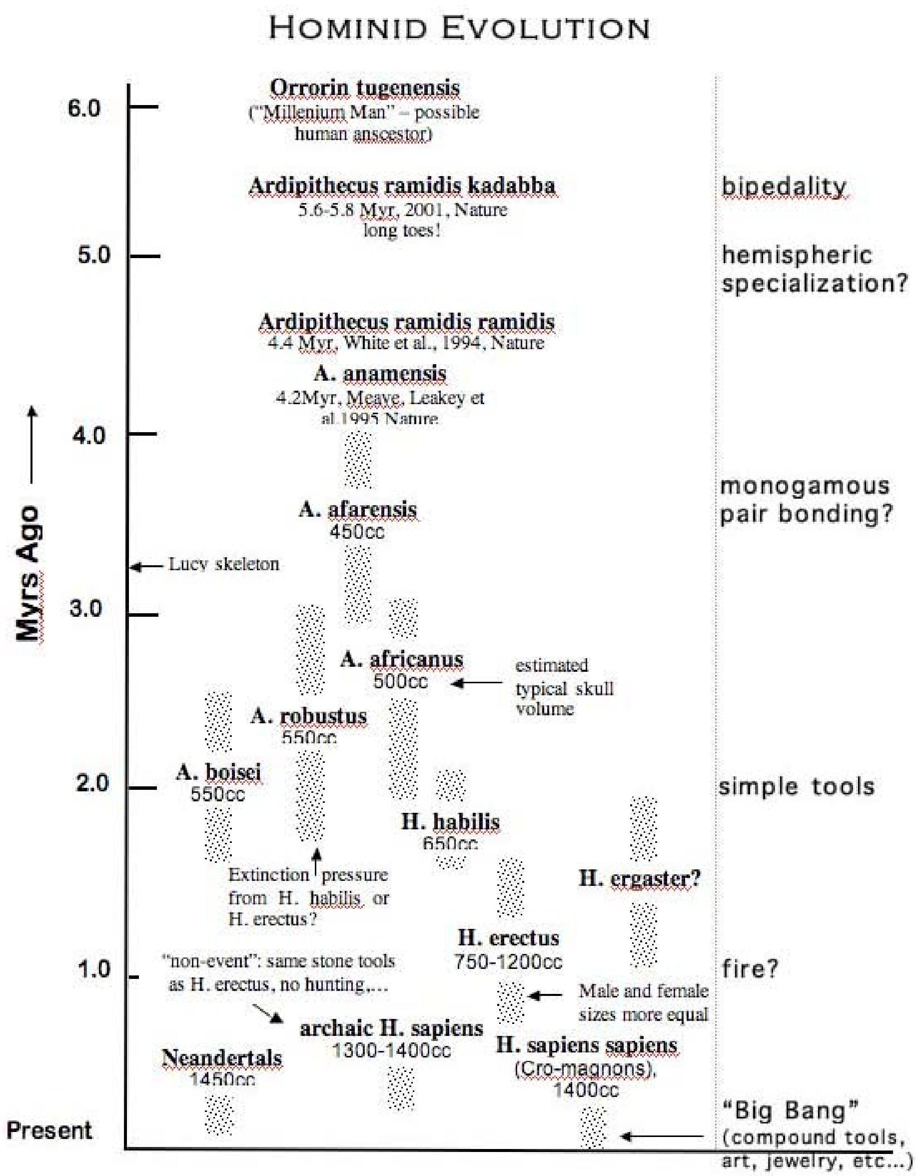
"Hairy Y" diagram based on current evidence suggests that traits other than bipedalism, such as sexual dimorphism, may be important in distinguishing hominids from their forerunners.

We don't care about details of this tentative geneology, but we certainly do want to know when certain traits first arose that have been associated with the later development of intelligence.

Among the most-suggested important factors are **bipedality, monogamous pair bonding, simple tools, ability to use chemical fuels (fire),** as well as more modern innovations, like compound tools, art, jewelry, etc. The diagram shown below indicates educated guesses for (roughly) when these events occurred. Notice that the diagram includes hominids, like Australopithecenes, various categories of the "Homo" line, eventually leading to **modern humans**. The latter "big bang" occurred less than about

0.1 Myr (100,000 yr) ago, when suddenly appeared cave paintings and jewelry and boats and fishing hooks, etc., so it appears at the bottom of the diagram.

An important point is that there is strong evidence for bipedality at least 5-6 Myr ago. Since bipedality is often associated with the increase in brain size that we associate with intelligence, that could have been a major transition—but no one knows why it occurred (trust me, even though you can find about 100 speculations in various sources).



The appearance of these traits in humans, and in pre-humans, brings up the question that is so important, but only to humans—whether humans are *unique* in some sense. We now list a few suggestions for the source of human uniqueness.

Human uniqueness?

We might be unique in bizarre ways, as are all animals, but our question is whether our way of *thinking* is unique. However it is likely that there were some crucial *prerequisite uniqueness factors* responsible for the "thinking." Some suggestions are summarized here.

There are a large number of suggested crucial factors for human uniqueness, from those named above to concealed female estrus to language. A brief outline of 18 of these is given in an Appendix of these notes (you won't be tested on it), which is available online at the course website (separately from these notes). A partial list is below—again this is just so you can see the variety. Don't memorize it. We will emphasize bipedality and how it may be related to brain development and language.

This is a large topic, so let's just stick with the textbook. It describes, concisely, a few traits of primates that have been suggested as important, even necessary, prerequisites for certain forms of intelligence.

Examples:

Ancestor of all primates was arboreal (lived in trees). These were prosimians (lemurs are one of remaining, and cutest, of them), perhaps 60 Myr ago, but also monkeys and gibbons (~ 30-40 Myr ago). Why significant for intelligence?

1. Limber arms from swinging through trees → throwing objects, use of tools;

2. Dextrous hands to hang from branches and manipulate food→ compound tools, … (Opposable thumb?) Note that compound tool use is no longer acceptable in a list of uniquely human properties, since several other animals (crows are apparently the most adept) are recognized as using some, perhaps primitive, form of the principle of using one tool to generate another.

3. Eyes of primates close together giving overlapping fields of view → depth perception. Early speculators also attributed human bipedality (perhaps, with language, the favorite candidate for an important and uniquely human trait) to our reliance on vision, but that idea is no longer in favor.

4. Primates have close parent-child bonds, children nearly helpless from birth for more years than offspring of any other species → increased chance for training and teaching in infancy, when the most important brain connections are developing. Even before symbolic communication, gestural, facial, and other possibly complex signals might become increasingly "processed" during infancy.

5. May also have been a factor in development of more **social cognition** in primates than other animals. However there is no longer room to argue for a discontinuity in social cognition between other animals and humans. Elephants are an excellent (and sad) example. Even octopi, perhaps one of the last creatures expected to display it, show that they possess at least rudimentary social cognition.

As explained in the textbook, the lineage from great apes to hominids to humans appears more and more complex, and will probably continue to do so. For example, there were apparently two, and possibly three, subspecies of humans on Earth until 30,000 (Homo neanderthalis) to 12,000 (Homo floresiensis?). Fossils discovered in 2004 in Indonesia…etc.

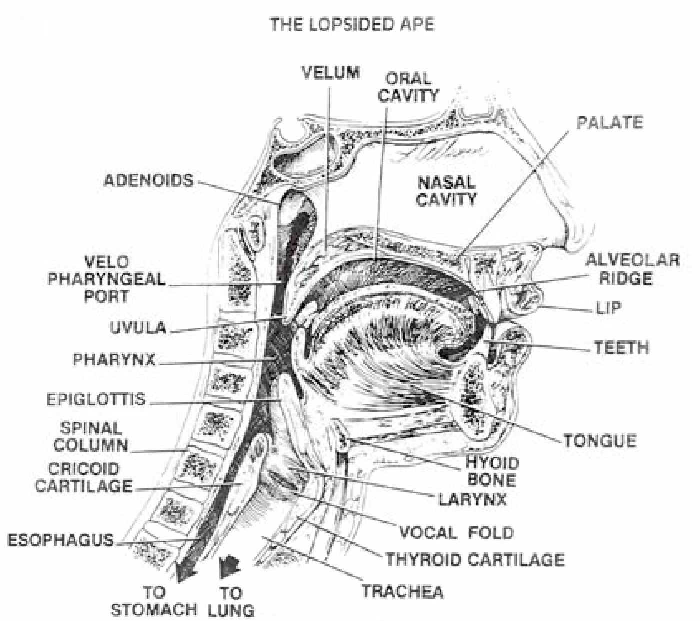
Other suggestions (don't worry about memorizing them—if you are interested in this subject, call me or email me after the semester is over and I will send you a ~ 5 page discussion of these that contains more detail.

● Foraging and scavenging in early hominids;
● Control of a chemical fuel (fire)—this is most interesting if correct, since fires require lots of oxygen in the atmosphere;
● Tools, especially compound tools (but crows, chimp termite hunting,…)
● Brain development—this is what your book, and we, will concentrate on.
● Bipedality—a long-time favorite: certainly preceded increase in brain size, freed hands for tools, signals, weapons, carrying (food, children), throwing (which may have required lots of brain energy for hand-eye coordination).
● Monogamous pair bonding
● Changes in stages of lifespan—especially premature birth of human children, leading to brain development exposed to environment. This is associated with big head (big brain) and small birth canal (bipedality).
● Varied sex-related behaviors—concealed estrus, continuous female receptivity, private copulation, sexual strategies,…
● An aquatic phase in hominid evolution. Explains lots, dismissed by most.
● Language—This is a major topic that would be considered in detail in a more serious and longer version of this course.
---Required complex vocal apparatus, unique in humans [nasal passages, larynx, tongue, diaphragm, associated muscles, throat structure, hyoid bone (possibly found in 60,000 yr. old Neanderthal)]
---Creates new categories and modes of thought; restricts others?
● Possession of certain types of "mental states"—self-consciousness, attribution of mental states to others, empathy, morality, ethics (but consider Stanley Milgrom…), social learning (but consider "genius" monkey Imo on Japanese island of Koshima in 1950s; also now octopi, others.)
● Art, music—large number of works claiming this; e.g. music as forerunner of language.
Domestication of humans (architecture, carpentered world), animals (first form of capital), plants (agriculture).
● Literacy (writing)—increased information storage, but many pitfalls also.

Bipedality

Many ideas about human uniqueness center on _*bipedality*_ (spending a large fraction of time in upright position) as being a fundamental human distinction, but there is no agreement on how or why bipedality came about, or on the most important of its many consequences (freed hands to build tools? But crows are now known to build compound tools. Allowed development of complex muscle and bone structure needed for language? Your text mentions some of these, and relates them to the fact that an early part of our lineage, the prosimians, spent millions of years living in trees. They don't stop to consider how that would probably make bipedality, and intelligence, very contingent. What is the probability that an exoplanet will have forests or something analogous

A favorite: **Premature birth**. Upright posture narrowed birth canal. Combined with big heads for big brains, this forces human infants to be born several months prematurely, so the brain undergoes neural development in the presence of environmental stimuli.



Schematic diagram of the principal organs involved in speech (from Calvert, 1980).

→ An important potential consequence of bipedality—freed up space for the development of varied and strong muscles around the jaw and throat. These would later make spoken **language** possible. The following picture should give you an of how difficult it might be to arrive at such a complicated end point. If language and thought are so intertwined, as many (mostly linguists) think, then *this* was perhaps THE crucial development that made human language possible.

Most people think that bipedality in humans probably arose *at least* around 4 Myr ago (known from fossils; infer from pelvic anatomy + Mary Leaky's 70 footprints of 3 hominids, etc.).

Within last month or so (Oct. 2008): **bipedality was discovered in octopi!** Unclear how often they use it (for camouflage in the cases seen so far), but it is interesting that the octopus, formerly considered a creature of very low "intelligence," has in recent years become more and more appreciated for its cognitive abilities.

The brain and intelligence

Undoubtedly the biggest focus in trying to understand the origin of our "intelligence" and how it is related to cognition in other animals focuses on the brain, as you might expect.

All this work focuses on some supposedly unique property of human brain development.

Examples:

---**brain weight/body weight** (see figure; sometimes called "encephalization") [But note that the distributions of relative brain size overlap between fish, reptiles, birds, mammals; i.e. *some* birds have relative brain size as large as in some primates.] Diagrams in book, alternates below.

---**expansion of cortex** (around 2 Myr ago, H.Erectus); but no discontinuity with other primates. [Cerebral cortex=80% of brain in humans, 74% in apes, 68% in monkeys, 50% in prosimians]

---**Other neural specializations** for, e.g. abstraction, categorization? (but cf. birds)

---**hemispheric specialization** (left-right brain laterality; foldings; modular functional structure). Surprise: probably occurred more than 4 Myr ago; also found in other species. Example is exerpt below.

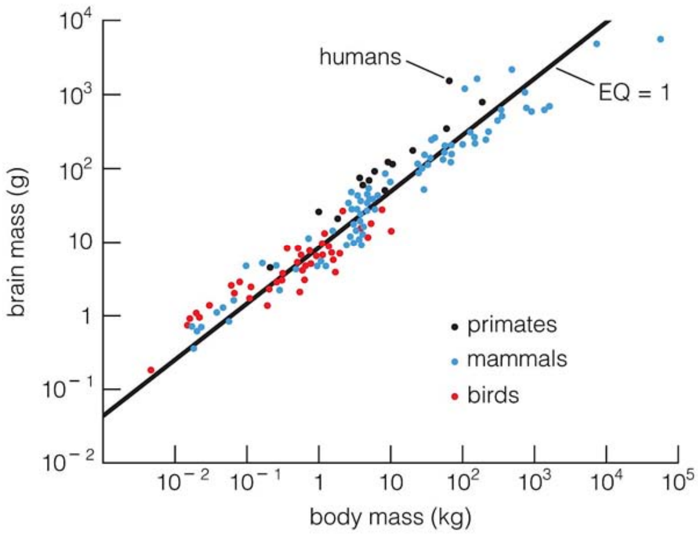
---**significant brain development after birth** (the idea is related to bipedality, which narrowed the birth canal, and the large heads we already had developed for our size. This results in human babies being born prematurely by a large margin.

One of the more important goals in this area is to find whether there really is some aspect of our neural architecture that is unique, discontinuously different from other animals. Unfortunately most of these are continuous with or have been found in other animals.

A recent example claims hemispheric specialization has been found in great apes:

Gillian Sebestyen Forrester et al. in journal *Animal Behavior*, 2008.

Encephalization Quotient (EQ)



Your textbook focuses on “**encephalization quotient**.” The idea that a larger brain will result in increased cognitive ability is not obvious—usually a larger brain comes with a larger body, and much of the brain’s activity is directed toward control of physiological function.

The graph from your book is shown on left (color), followed by an alternative graph; both of them show that humans, along with porpoises, have the largest departure from the mean relation. The advantage of the second version is that different animals are identified.

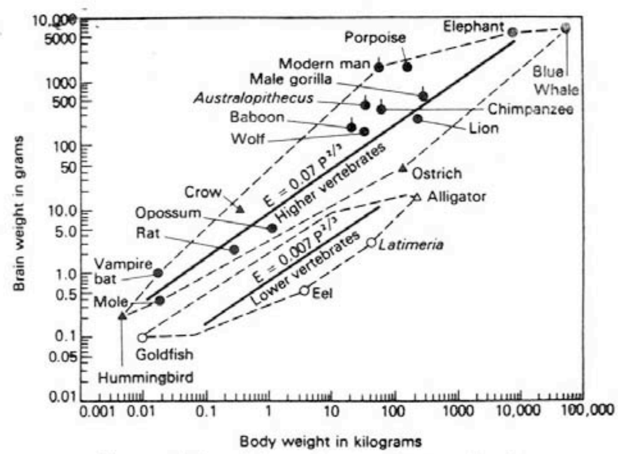
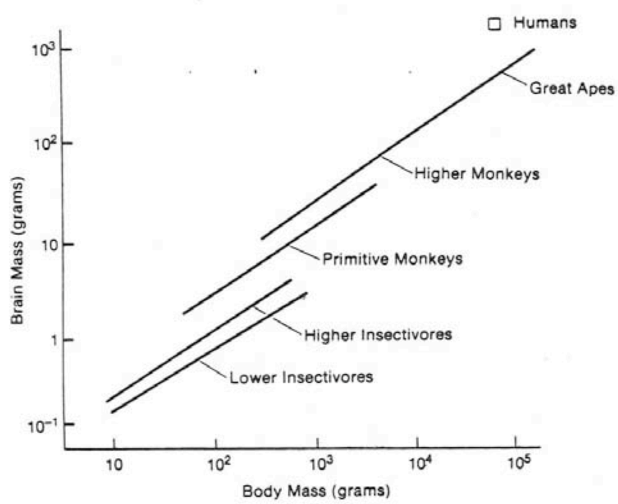


Figure 2 Brain weight as a function of body weight (from Jerison, 1973; see p. 132)



Your book gives an extremely interesting and up-to-date graph showing the evolution of encephalization quotient in whales and dolphins. Here is a comparison between hominid estimated encephalization quotients and those of dolphins and porpoises.

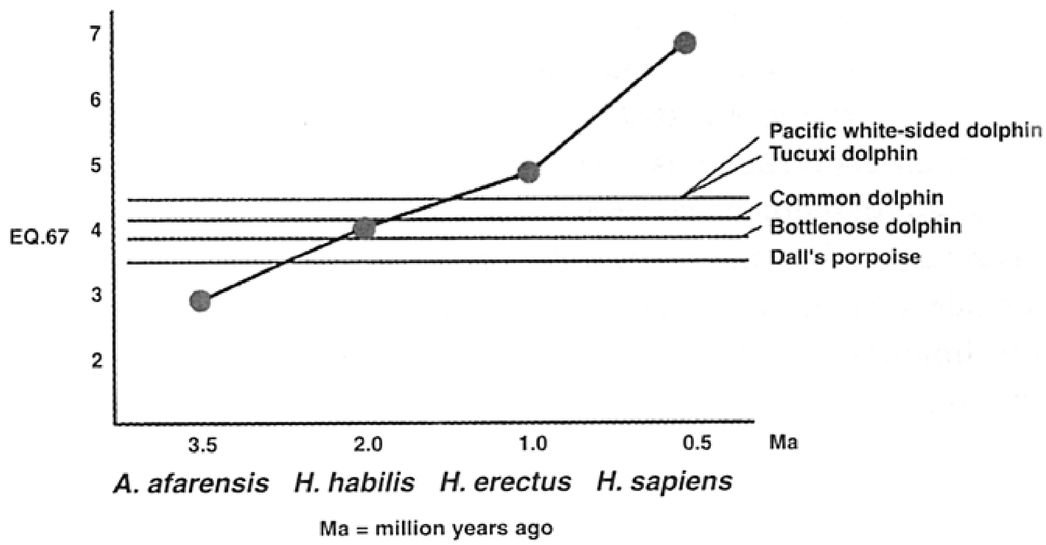


FIGURE 9.3 A comparison of encephalization quotients, calculated as the ratio between brain and body sizes to the expected component of 0.67, a porpoise (*c*. 3.5), four species of dolphin (*c*. 4.0–4.5), and the increasing values in the hominid lineage from the australopithecines to modern humans. Note hominid EQ only pulls past that of the biggest-brained dolphins about 1.5 Ma ago. (Redrawn from fig. 3 of L. Marino (1996; citation is in note 92) with the permission of the author.)

END OF NOTES