

## Anthropogenesis

The universe did not give birth to life nor the biosphere to man. Our number came up in a game at Monte Carlo. It is not surprising that, like the man who has just won a million, we still feel the strangeness of our condition.

—Jacques Monod, *Chance and Necessity*

The earliest writings bear witness to the deep anxiety human beings have always experienced concerning their origins. In Genesis we read that “from the clay of the ground the Lord God formed man, breathed into his nostrils the breath of life, and made man a living person.” The clay referred to by the scribes of the desert is composed of atoms, and only atoms. So is man. Had the scribes already realized the material nature of man? Their knowledge was still too limited for them to explain the metamorphosis of clay into a living being. But mental images and concepts came together and were combined in their brains. It was a sculptor who had realized the unprecedented in giving life to a clay statue. This symbolic vision, this mental object, calmed the anxieties of a large segment humanity for several thousands of years.

Since the era of the *Encyclopedia*, that most important landmark in the history of ideas, observed data have accumulated. Comparative anatomical studies of living creatures suggested to Jean-Baptiste de Lamarck his theory of an evolutionary “descendance” of species. In geological strata, the fossil remains of extinct species, and later those of the direct ancestors of man, were found. New techniques became available to date these “documents” of the past objectively. Molecular biology revealed differences and similarities in the ultimate material of heredity, DNA. The slow and erratic progress of biological evolution, conforming prosaically to the laws of thermodynamics, replaced the vision of the sculptor’s gestures and his imaginary life-giving breath.

In the light of our current knowledge, the very recent differentiation of *Homo sapiens* stands out as a veritable planetary “phenomenon,” to use Pierre Teilhard de Chardin’s word. For an observer who wishes to be objective, the phenomenon is certainly not the descent of some “spirit” into the brain of a distant ancestor of man, but the gigantic transformation of the earth’s surface accomplished by a single, unique animal species. Swarming over all dry land, this species has disrupted and destroyed in a few thousand years virtually the entire environment that gave birth to it. This power of domination “of the fishes in the sea, and all that flies through the air, and all the living things that move on the earth,” including obviously his fellow beings, is due to man’s brain. Let us examine the process by which, over a few million years, this “phenomenal” development of *Homo sapiens* came about.

## MONKEY CHROMOSOMES

In 1809 Lamarck ended the first part of his *Zoological Philosophy* with “some observations relative to man,” in which he suggested that “during a series of generations . . . an ordinary race of quadrupeds” was “transformed into bipeds.” About fifty years later, in 1863, Thomas Huxley, a zealous neophyte of the newly emerging Darwinist school, took up this idea in the light of Darwin’s own *Origin of Species*, published in 1859. The storm broke loose. Man was descended from the monkey! Two centuries earlier, Father Vannini had been burned alive in Toulouse for stating the same thing. Today, the idea is no longer so fearsome. We limit ourselves prudently to stating that humans and monkeys have common ancestors. Their chromosomes bear undeniable witness to this, just as much as the shape of their skulls or their brains.

It is not very difficult to observe the chromosomes of a human being or a monkey under the microscope. A blood sample is taken and the white cells cultured. They divide, and their chromosomes separate into well-defined rods. Once dispersed they are easily stained and identified. In American monkeys the diploid number varies from twenty to sixty-two. It is much more consistent in Old World monkeys. The most closely related to humans—the orangutans, gorillas, and chimpanzees—all have forty-eight chromosomes. Humans have only forty-six. Does this mean that we have a pair of chromosomes less than the apes? Not

at all (Figure 73). High-power examination of stained chromosomes brings out an alternating pattern of light and dark bands, whose thickness and distribution varies from one segment of the chromosome to another. Altogether there are almost a thousand bands that can be compared in these various species. An early discovery was that the

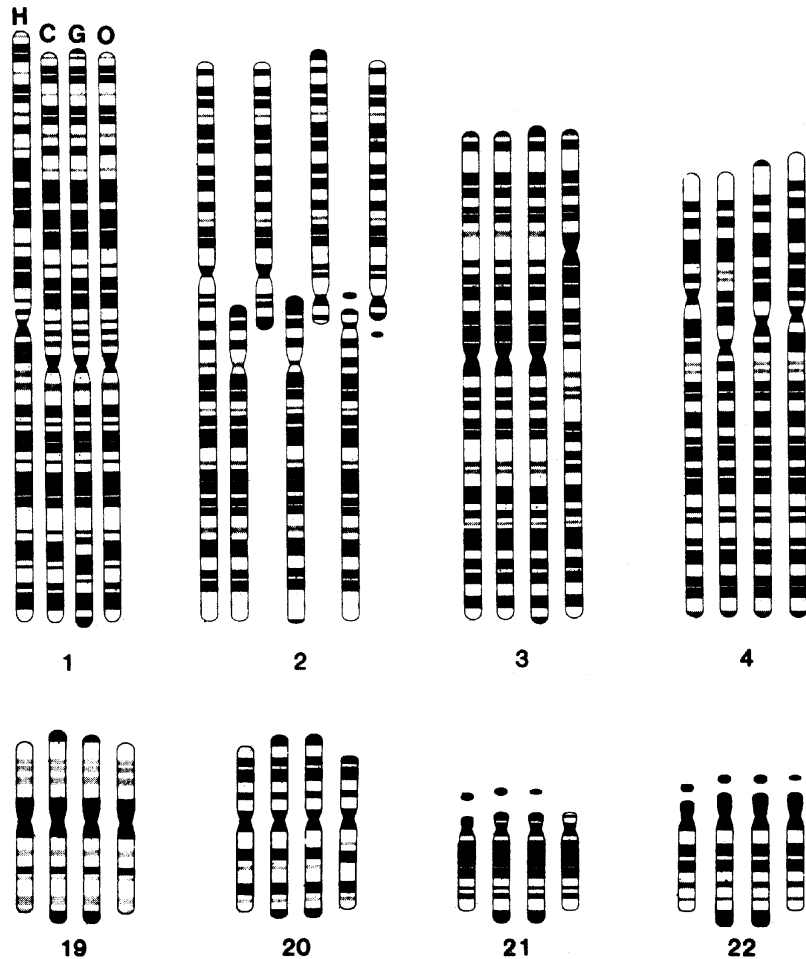


Figure 73. Comparison of selected chromosomes (numbers 1 to 4 and 19 to 22) in humans (H), chimpanzees (C), gorillas (G), and orangutans (O). The chromosomes were stained to demonstrate their banding. The similarity in the distribution of the bands is striking. In humans, chromosome number 2 results from the fusion of two chromosomes (2p and 2q) present in chimpanzees, gorillas, and orangutans. Only differences in detail distinguish the four species. (From J. J. Yunis and O. Prakash, 1982.)

pattern of these bands is strikingly constant in the orangutan, gorilla, chimpanzee, and man.<sup>1</sup> The chromosomal relationship between the four species cannot be doubted. A second finding was that humans had not lost any chromosomes. The characteristic bands of *two* chromosomes of the ape could be found in a *single* human chromosome, number 2, which results from the end-to-end fusion of the 2p and the 2q chromosomes of the ape. Five chromosomes seem completely identical in the four species. The others differ slightly, mainly by the inversion of certain chromosome segments, as if some fragment had broken away and become reincorporated the other way around. More rarely, small chromosome fragments actually disappear.

A comparative map of these structural alterations can be drawn. The presence of the same transformation in two different species signifies a common ancestry. On this basis the orangutan seems the furthest from man and the chimpanzee the closest. A genealogical tree grows up. The central trunk groups the chromosomal characteristics common to all four species. It represents a long-disappeared "hominoid" ancestor. Then there are diverging branches for first the orangutan, then the gorilla, the chimpanzee, and finally man (Figure 74).

The order of the branches of this hypothetical genealogical tree is still the subject of lively debate. This does not matter. The species alive today represent only a few typical specimens of a flourishing, multiple

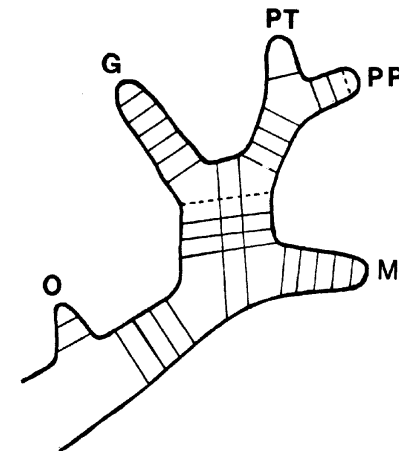


Figure 74. Genealogical tree, drawn on the basis of chromosomal differences between the orangutan (O), gorilla (G), two chimpanzee species—*Pan troglodytes* (PT) and *Pan paniscus* (PP)—and modern man (M). Each line represents a chromosomal change. (From B. Dutrillaux, 1981.)

ascendancy. The striking analogies of their chromosomes are very significant. In spite of the reorganizations just mentioned, their genetic content is very similar. Since the work of Thomas Hunt Morgan on the fruit fly *Drosophila* (see Chapter 6), we know that each band represents a gene or a well-defined group of genes.<sup>2</sup> Here, on chromosome number 1, we find the structural gene of the enzyme enolase 1; there, on chromosome number 11, that of the enzyme lacticodehydrogenase A. In this way almost 400 genes have been located on the human set of chromosomes. Comparisons with the great apes have been made for about only forty genes, but so far they have practically all been found on the same chromosomes.<sup>3</sup> These striking similarities have been confirmed by other biochemical data.

For example, DNA, the genetic material, has been compared in chimpanzee and man using a molecular hybridization technique.<sup>4</sup> The DNA molecule is made up of two complementary strands in the form of a double helix (see Chapter 6). Under the right conditions, they dissociate and reassociate spontaneously *in vitro*. When strands taken from a chimpanzee are mixed with strands from a human being, they reassociate to form hybrid "man-monkey" molecules, differing from the natural DNA of each parent in only about 1 percent of their length. Some researchers have even proposed that the homology between non-repetitive DNA sequences in the chimpanzee and man is virtually complete!

Logically, these homologies are repeated in the proteins coded for by DNA. The complete amino acid sequence of six proteins, including the alpha and beta chains of hemoglobin, is *exactly* the same in chimpanzees and humans. One substitution is found in delta-hemoglobin and myoglobin and a few more (three to eight) in much larger molecules such as carbonic anhydrase or transferin. In 1975, after examining forty-four proteins using rapid, high-resolution techniques, M. C. King and A. C. Wilson estimated that the mean difference between amino acid sequences in proteins of chimpanzees and humans did not exceed 0.8 percent. The well-known A, B, and O blood types used by anthropologists in their studies of human groups are identical with those of the chimpanzee, as is the Rh factor.<sup>5</sup> Based on structural data of this type one can estimate, at least on an empirical level, the genetic distance between chimpanzees and humans. It is only twenty-five to sixty times greater than that between human populations of Caucasians, Africans, and Japanese!

Everyone therefore agrees that, genetically speaking, the chimpanzee and man are very close. However, their brains and, above all, their cerebral functions differs markedly.

## FOSSIL PUZZLES

From the shrew to man, the weight of the brain relative to that of the body increases spectacularly (see Chapter 2). If we arbitrarily set the index of encephalization at 1 in the shrew, it is 11.3 in the chimpanzee and 28.7 in man. The neocortex develops even more rapidly. Its progression index, set at 1 in insectivores, jumps to 58 in the chimpanzee and 156 in man. Other regions of the brain do not follow the same evolution. Indeed some, like the olfactory bulb, move proportionately in the opposite direction. How has this "corticalization" of the brain come about?

The only "documents" available are fossils. During fossilization, the soft tissues, particularly the brain, disappear. Only the bones are preserved. We must revert to Franz Joseph Gall's craniology, discussed in Chapter 1, and examine the skull and the imprints of the blood vessels in it, to reconstruct the cranial cavity and assess its volume, which fortunately is always quite close to that of the brain. We are, however, far from direct observation of the brain and its convolutions.

Since the discovery of *Pithecanthropus* in 1891 by the young military physician Eugene Dubois, the remains of "fossil man" or the hominids have been grouped into three genera: *pre-Australopithecus*, *Australopithecus*, and *Homo*. Recent authors further distinguish two species of *Australopithecus* and three of *Homo*: *Homo habilis*, *Homo erectus*, and obviously *Homo sapiens*.<sup>6</sup> Before discussing this subject, it is important to note that this nomenclature is based on a limited number of individuals. Only eleven *Australopithecus* skulls have been measured, five of *Homo habilis*, and twenty of *Homo erectus*. Already the boundaries between these species are contested because of a few intermediate specimens. Future discoveries will probably lead to revisions, but the known specimens provide enough of a yardstick to draw a preliminary genealogical tree of our fossil ancestors.

Many species of primates were abundant in Africa during the thirty million years before our era. The first hominids appeared in the same regions about four million years ago or, according to certain authors,

perhaps five or even seven million years ago! These predecessors of *Australopithecus* already used their hind limbs for walking. Their faces showed the first signs of becoming more “delicate” than those of the apes and their molar teeth were less incisive; above all, their cranial capacity, at 400 cubic centimeters, was comparatively enormous, although it remained less than that of a chimpanzee. Later came the real *Australopithecus*, whose features were even less apelike. Their height was between 1 and 1.5 meters (depending on the species), and their cranial capacity—from 400 to 550 cubic centimeters—began to overtake that of the chimpanzee and approach that of the gorilla. They first appeared about three and a half million years before our era and disappeared only about a million years ago.

At about the same time, three to four million years ago, the oldest known members of the genus *Homo* appeared. These members of *Homo habilis* were completely bipedal and were larger than *Australopithecus*. Their teeth were adapted to omnivorous eating habits. Their cranial capacity was, on average, about 650 cubic centimeters, but occasionally reached 750. About one and a half million years ago, these skillful (“habile”) hominids were succeeded by *Homo erectus*—the *Pithecanthropus* whose existence had been predicted by Ernst Haeckel in 1874 (he had invented the name before the species was discovered). The cranial capacity of *Homo erectus* was between 800 and 1,200 cubic centimeters, or even more for those specimens still surviving less than half a million years ago. His hands were like those of modern man.

Then, as Yves Coppens described it in 1981, “*Homo sapiens* arrived inconspicuously, so inconspicuously that the boundary between *Homo erectus* and himself varies and even varies a lot according to different authors!” The capacity of his skull ranges in various specimens from 1,200 to 1,400 cubic centimeters and reaches a mean value similar to that of modern man (see Chapter 2). Meanwhile, Neanderthal man, considered a subspecies of *Homo sapiens*, appeared in Europe and in the Near and Middle East. Curiously enough, the internal volume of his skull—from 1,550 to 1,690 cubic centimeters—is slightly more than the mean value found for modern *Homo sapiens*.

Within a few million years, the brains of man’s ancestors tripled in volume. Did the complexity of their cerebral organization increase proportionately, or, on the contrary, did it evolve independently?

Careful examination of the skulls of fossil man brings to light morphological transformations that reflect a profound evolution in the orga-

nization of the brain within. There is an increase in the height of the brain above the cerebellum, a preferential development of the frontal lobe, and a proliferation of the grooves and folds corresponding to the cortical convolutions. In addition, the imprints left by the blood vessels on the inner surface of the skull show a marked enrichment in the vascularization of the meninges, the membranes that enveloped the brain, and thus of the brain itself (Figure 75).

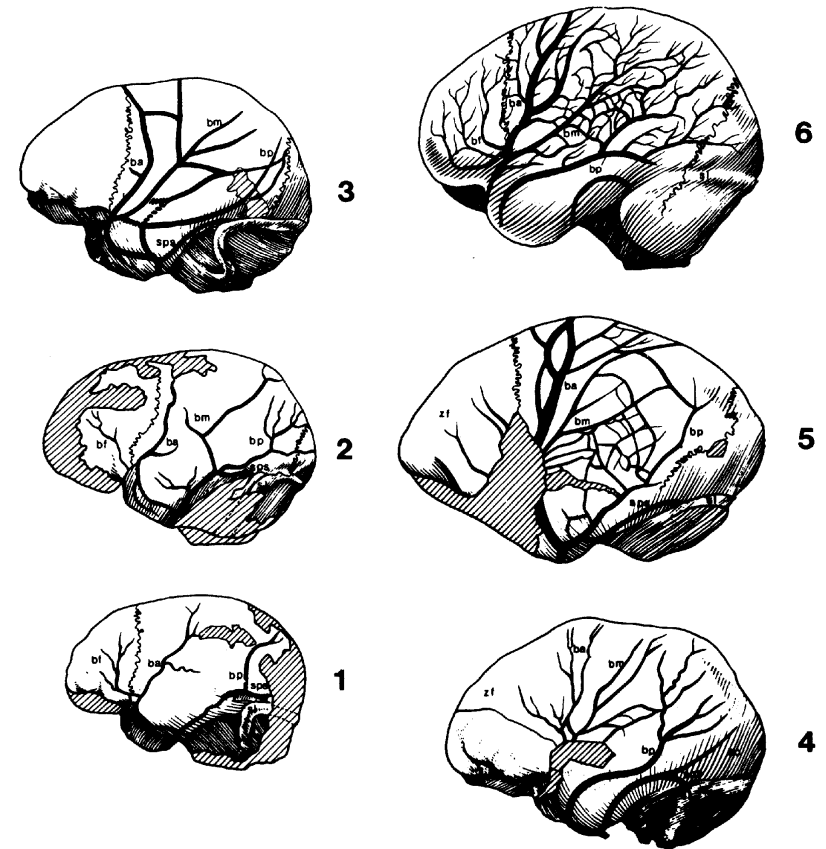


Figure 75. Casts of the inside of the skulls of man’s fossil ancestors permit the reconstruction of the blood vessels that irrigated the membranes enveloping the brain—the meninges. The pattern becomes markedly more complicated from *Australopithecus africanus* (1) and *Australopithecus robustus* (2) to modern man, or *Homo sapiens sapiens* (6), after progressing through *Homo habilis* (3), *Homo erectus* (4), and *Homo sapiens neanderthalensis* (5). (From R. Saban, in Y. Coppens, 1981.)

The “industries” of our ancestors also bear witness to their cerebral functioning. The oldest known stone tools, discovered in Ethiopia by Chavaillon in 1969, date from two or three million years ago. These broken quartz fragments, with a few artifactual finishing touches, have been found near the remains of *Australopithecus*, who seems to have been responsible for making them. *Homo habilis*, as his name indicates, developed the manufacture of stone tools, cut to form a sharp edge. He built stone shelters and made use of red ocher. *Homo erectus* was the first to make the typical bifacial stone tools called Acheulean (from the name of the place where they were discovered, Saint-Acheul, near Amiens in France). He also knew how to use fire for domestic purposes. Finally, there came a rapid cultural advance with *Homo sapiens*—the first to bury his dead systematically and thus to pose questions about his own nature.

It is comforting to note that the development of human, and even prehuman, industries went hand in hand with the evolution of the brain. Nevertheless, as one might expect, the correlation between the evolution of cerebral morphology and advances in the technology of tools is not perfect. Shaped stones are typically found with the remains of *Homo habilis*, but also with those of *Homo erectus*. Sometimes *Homo sapiens* used Acheulean axes, like those usually manufactured by *Homo erectus*. Was biological evolution in advance of cultural evolution as Coppens suggested? Or did certain peoples already show a technological conservatism? Will we ever know?

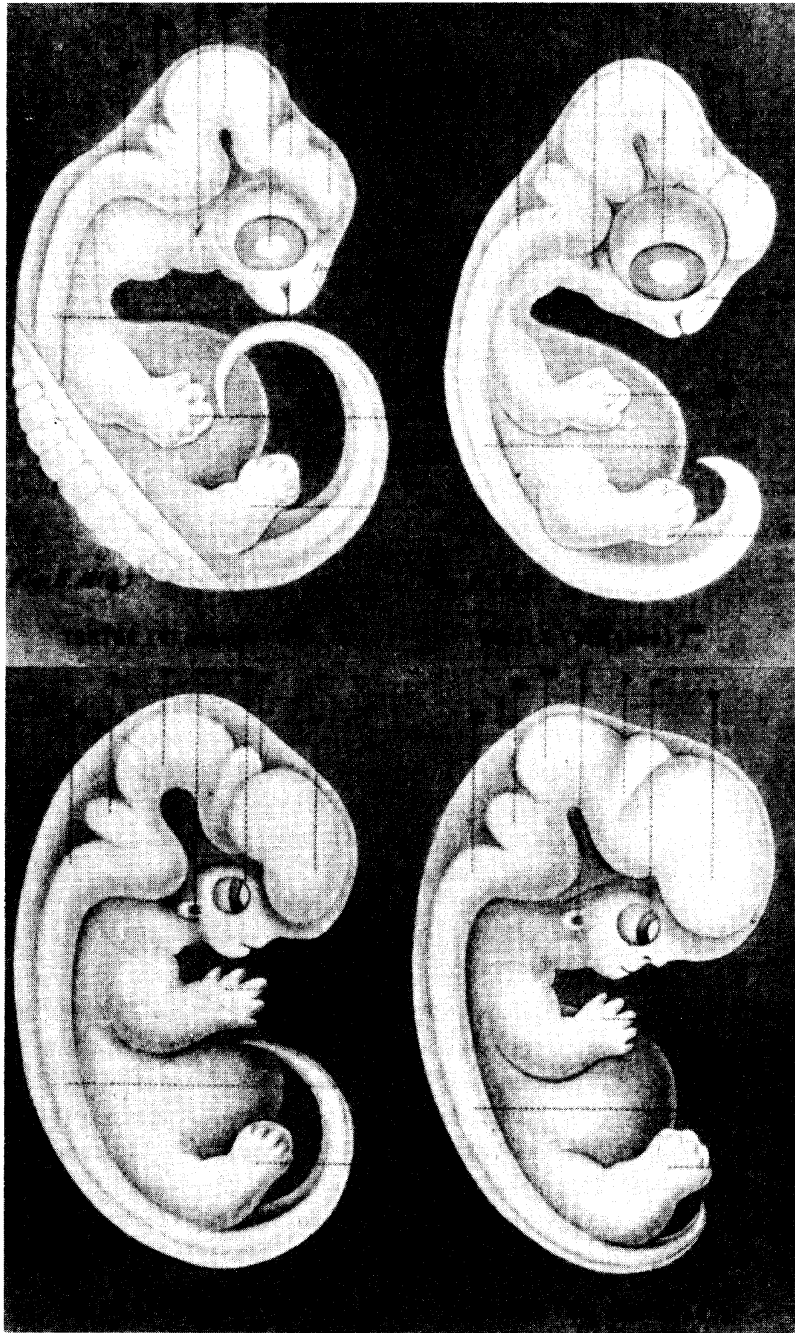
In the same way, any commentary on the linguistic abilities of these fossil hominids falls automatically into the realm of speculation. As we saw in Chapter 7, handedness and specialization for language *can*, although rarely, be situated in different hemispheres. Manual skill and precision are not necessarily associated with the use of language. Nevertheless, the making of a tool of a specific shape requires a “mental representation” of that shape and the working out of a strategy of how to realize it. Thus, the faculty involving imagery and conceptualization was already well developed in the brain of *Australopithecus*. They must have been capable of communication between themselves by the use of signs, but did they already use a varied repertoire of sounds, the rudiments of the first spoken language?

## THE WINKS OF THE YOUNG CHIMPANZEE

The phenomenal development of the cerebral cortex in man’s fossil ancestors is just one more illustration, although a very spectacular one, of the paradox of the nonlinearity between the evolution of the genome and that of the brain (see Chapters 6 and 7). This paradox takes on its true dimensions if one recalls recent discoveries in molecular genetics. Not only are most structural genes of the chimpanzee also found in man, as we have just seen, but equally in cats and mice. Moreover, their spatial relationship on the chromosomes is preserved from cat to man.<sup>7</sup> It seems that we must admit that this evolution took place on the basis of a relatively small number of genetic mutations and chromosomal reorganizations. Obviously, no major disruption of the genetic material accompanies the development of the human brain.

So what happened? Clearly, we cannot go back in time to find out, but must we therefore abandon our search for traces in the genes of the evolutionary process? Ernst Haeckel, whose importance in the history of ideas is comparable to that of Charles Darwin, showed us in 1874 that one way of proceeding is to understand the link between the evolution of a species, or *phylogeny*, and an individual organism’s embryonic development, or *ontogeny*. According to him, the “connection between the two is not external or superficial but deep, intrinsic and causal.” It does not matter whether phylogeny caused ontogeny, as Haeckel suggested, or the opposite.<sup>8</sup> Probably it went both ways. More important are the openings offered by present and future developments in molecular genetics toward an understanding of Haeckel’s “connection.” One approach is through a comparison of the modes of gene expression during ontogeny.

Karl von Baer in 1828, and later Haeckel, quite rightly drew attention to the striking resemblance of the first developmental stages of the fetus from the tortoise to man (Figure 76). The major differences appear in the final stages of development. From reptiles to primates, these are mainly expressed in the enormous expansion of the neocortex. This observation led to the quite legitimate hypothesis that the evolution of higher vertebrates took place through the addition of extra stages in their ontogenetic development. To the extent the initial stages persisted, there was a “recapitulation” of the evolution of the species during the embryonic development of the most evolved organ-



isms. Thus, the mammalian embryo would pass through “fish” and “reptile” stages.

This law is subject to exceptions. Stephen Gould turned his attention to cases in the animal kingdom suggesting an evolution in the opposite direction. The evolution of the skull and the face in higher primates and man seems to be one of these exceptions. The head of a young chimpanzee and that of the human child are similar. Even more astonishing is the resemblance between an *adult* man and a *young* chimpanzee, whose simian features develop only as it grows older (Figure 77).<sup>9</sup> Should one conclude that the chimpanzee has undergone a final addition of a monkeylike face to a more humanlike common ancestor? Does the chimpanzee descend from man? Or, on the contrary, has there been a final deletion in the adult human, due to an arrest of skull development, thus leading to the persistence of fetal features? The known fossil remains of man’s direct ancestors, *Australopithecus* or *Homo habilis*, are unquestionably pithecoïd. The adult simian features gradually disappeared, and the similarity with the young chimpanzee became more striking. It seems as if its features became transformed into those of man, as if what is a transitional stage in the ontogeny of other primates became a terminal stage in man.<sup>10</sup> As far as the shape of the body, especially that of the skull, is concerned, man resembles the fetus of a chimpanzee suddenly become adult. He is “neotenic.”

Is this theory enough to explain the transition from the head of a monkey to that of man? Obviously not. Another characteristic feature of the development of the human skull and brain is that it continues long after birth. This rule is quite independent of the previous one. The “morphological” development of the skull stops when its proportions are similar to those of a fetal chimpanzee, but absolute growth in size continues. The cranial capacity of the chimpanzee increases by only 60 percent after birth. In contrast, that of man increases more than fourfold. In *Australopithecus*, values intermediate between those of chimpanzee and man have been estimated.<sup>11</sup>

Although the gestation periods for chimpanzees and humans are very similar (respectively, 224 and 270 days), the volume of the brain reaches 70 percent of its final value during the chimpanzee’s first year, whereas this percentage is reached only after about three years in

Figure 76. Comparison of the embryonic cerebral vesicles in four vertebrate species. From left to right, top to bottom, we see the tortoise (sixth week), the chicken (eighth day), the dog (sixth week), and man (eighth week). The resemblance is clear. (From E. Haeckel, 1874.)

humans.<sup>12</sup> Thus, the volume of the brain continues to increase long after birth in man.

Can the evolutionary development of the human brain be completely explained by neoteny and prolonged maturation? The reply is still no. The development of the brain, particularly of the cerebral cortex, must not be confused with that of its bony case. The similarity in the proportions of the skull or the face of the newborn chimpanzee and the adult human is totally unrelated to the content inside. No one will argue that the brain of the newborn chimpanzee is closer to an adult human brain than the brain of its own parents. Nor does the prolonged postnatal increase in cranial capacity suffice to make a

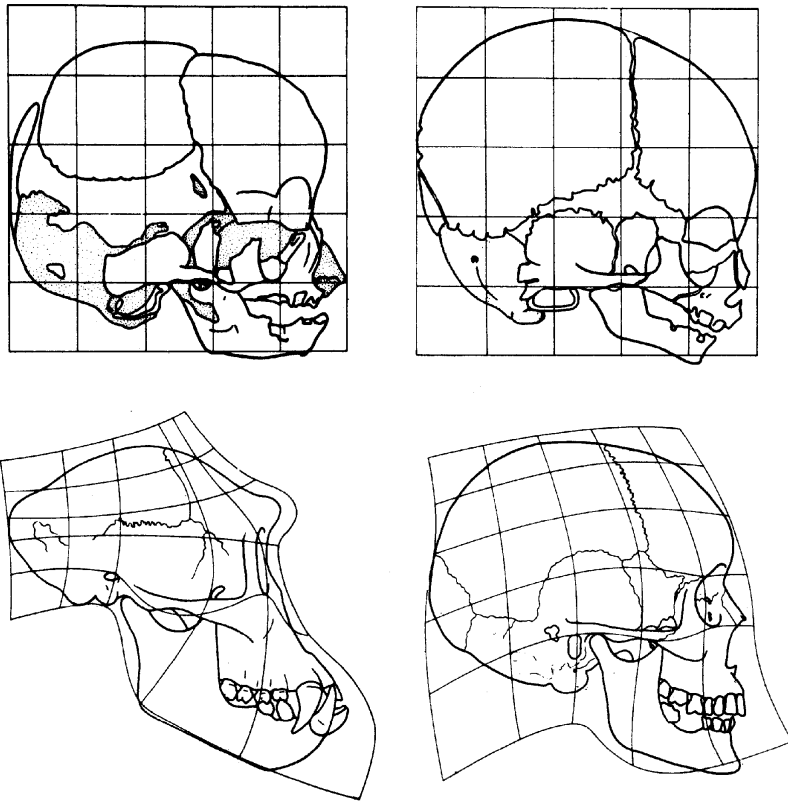


Figure 77. Comparison of skulls of the chimpanzee (on the left) and modern man (on the right) in the fetus (top) and the adult (bottom). The fetal skulls are much more similar than the adult ones. But the adult skull is much closer to the fetal skull in man than in the chimpanzee. (From D. Starck and B. Kummer, 1962.)

man. In the rat it increases 5.9 times, which is more than in man!

Anatomical observation shows that the cortical surface area increases from 500 square centimeters in the chimpanzee to more than 2,000 square centimeters in man. All cortical neurons are formed before birth in the chimpanzee as in man. Man differs from the great apes in having a large additional contingent of neurons, and this feature is genetic. In the same way, the relative surface area of the frontal cortex (whose importance in the genesis of mental objects was discussed in Chapter 5) increases from chimpanzee to man, and this is already determined before any contact with the outside world.

These anatomical facts are supported by behavioral observations. The gestures and expressions of the young chimpanzee are astonishingly similar to those of the young human infant.<sup>13</sup> The monkey manifests the same six stages of sensorimotor development that Jean Piaget and his followers have described in children.<sup>14</sup> Like children of two to four years, chimpanzees in the zoo play construction games with cubes of different shapes and colors, but they do not progress much further. In humans, development continues through a series of successive stages, during which the child elaborates patterns of reasoning, initially concrete and then progressively more and more abstract and universal. These operations on mental objects are over and above the cognitive development of the chimpanzee.

At the same general level one can include the oft-cited example of the young baby's smile. The monkey grimaces but does not smile. The human baby smiles, but this smile is not simply an imitation of the mother's smile. A natural experiment provided by premature babies proves this. They develop in a perinatal environment that is very different from the mother's womb. They come into contact with the outside world much earlier than infants born at term. Do premature babies smile at their "legal" age or, on the contrary, at their real biological age? The observations are unambiguous. They smile at the same biological age as full-term infants.<sup>15</sup> The child's smile is biologically determined.

It is true that the skull of an adult human resembles that of the young chimpanzee. But this neoteny cannot explain the extension of the cortex, the prolonged postnatal development, or the cognitive development of the newborn baby. All these features can be considered as a series of *final additions* to the monkey's ontogeny. How can they be explained genetically?

## GENES FOR COMMUNICATION AND SELECTIVE STABILIZATION

The "comparative anatomy" of DNA is still too incomplete to enable us to discern with certainty the set of genes that participates in the final phylogeny of the brain. In Chapter 6, when we discussed the power of genes, we saw that during ontogeny sets of genes were expressed differently from one cell to another and from one tissue to another in the embryo. Communication between cells plays a critical role in the coordination of this genetic expression in the "embryo system." This communication is itself under the control of genes that have no equivalent in unicellular organisms like bacteria. Their activity provides a vehicle for intercellular communication and sooner or later intervenes in the internal regulation of all embryonic cells. In the end, these "communication genes" are the regulating genes of regulatory genes! Insofar as neurotransmitters and hormones control the expression of genes in developing nerve cells, the genes controlling the synthesis of these chemicals are communication genes. The same is true of genes that govern the development of cell lines into nerve tissue or those that ensure firm contacts between cells of the first embryonic morula.<sup>16</sup>

Mutations of these communication genes can have such important morphological effects that the brain can be completely suppressed (see Chapter 6)! Can we see in them the "connection" that Haeckel suggested between ontogeny and phylogeny? It seems legitimate to propose that the evolution of the brain in our ancestors involved differential activity in the genes of embryonic communication.<sup>17</sup> Considering that their effects would be amplified, mutations in some of these genes could account for a dramatic morphological evolution.

Can one go further in defining these genes? Let us return to the more general problem of the evolution of the nervous system, not only in vertebrates but in the entire animal kingdom. The nineteenth-century evolutionists had the *sang-froid* to draw up genealogical trees of all living species on the basis of simple morphological criteria (which must obviously have counterparts at the level of the genome). The common ancestor of invertebrates and vertebrates was often imagined as a sort of worm, resulting from a repetition of identical fragments, or metameres. At the dawn of evolution, a few communication genes must have been enough to stimulate the development of a *redundant* organization of this type from a single metamere. Such an organization is still

found today in annelid worms, like the earthworm, whose nervous system consists of a series of cellular aggregates, or ganglia, all identical. As we progress from worms to mollusks and insects, redundancy is gradually lost. The final result, as we saw in the sea slug *Aplysia*, is a nervous system in which practically every neuron differs from its neighbors in its state of differentiation, in the "map" of the genes expressed (see Chapters 2 and 5). Thus, in invertebrates, the evolution of the nervous system has passed through successive stages of redundancy and diversification. Present-day species, in testimony to this evolution, have each successive stage fixed in their genes.

In the vertebrates, the evolution of the nervous system took a different direction. It began with an accident. Instead of forming from a solid chain of cells, as in the invertebrates, the nervous system developed from a hollow tube. This "discovery" may seem insignificant, but it influenced subsequent events. A hollow tube can "swell" by increasing the surface area of its walls, something that cannot happen in a solid cylinder. The neural tube of vertebrates indeed expands into successive vesicles, found from fish to man (see Figures 13 and 76). Some of these vesicles become much larger than the others. The most anterior one forms the cerebral hemispheres; the most posterior, the cerebellum. Both undergo an explosive development in the primates, accounting for almost all the cranial content in man. This increase in surface area can be compared to the stage of redundancy at the beginning of the evolution of the nervous system of the invertebrates. There are, however, differences in detail. There is no longer a repetition of ganglia in a linear chain, but rather a two-dimensional development of "cellular crystals" (see Chapters 2 and 6), which grow along their edges without changing in thickness. The example of the cerebellum is particularly significant in this respect. As we have seen, it is made up of five major categories of neurons organized in three distinct layers. Although the number of cell categories and their layered organization does not change as we progress from rat to man, the total number of neurons in the Purkinje cell category increases from 0.35 to 15 million. An enormous increase in cell redundancy accompanies the increase in area.

There is no shortage of genetic models for this evolutionary step. In the mouse, the "dwarf" mutation causes an impressive reduction in body size, with a 70 percent loss of weight without a change in body proportions.<sup>18</sup> The brain is also affected, losing a third of its weight and a fifth of its cells. The defect is due to an extremely low level (a

thousand times less than normal) of growth hormone, or somatotropin. But the brain seems relatively protected. The receptor “locks” in the brain (see Chapter 3) seem to be more efficient in “capturing” this hormone than the rest of the body. Logically, one might imagine that, if the level of growth hormone remained normal, such an increase in receptor efficiency might lead to a differential increase in the size of the brain and perhaps of the neocortex.

Certain congenital malformations in humans provide an example of how this differential growth could take place. Some children at birth have a brain weighing between 18 and 60 grams, or ten to twenty times less than that of a normal infant, born at term.<sup>19</sup> These “microbrains” have the same convolutions as the normal brain, and the cortex has the normal six layers of cells. Even the number of neurons in a vertical column of the cortex is the same as in normal infants. However, the number of these columns *across* the the cortex is greatly reduced. It seems that the tangential proliferation of embryonic neurons in the walls of the cerebral vesicles is affected, leading to a dramatic reduction in cortical area. Obviously, if we contemplate the opposite effect, the result would be an increase in the area of the cortex. A few mutations in communication genes, or chromosomal changes,<sup>20</sup> might then be sufficient to elicit a spectacular increase in redundancy in a given species.

An increase in surface area would of course have repercussions on the axonal and dendritic trees of cerebral and cerebellar cortical neurons. Already in 1909 Ramón y Cajal mentioned that in man these trees developed principally during the first few years after birth. At the time language develops, this growth is not yet finished. Because of the relative length of the period of synaptic proliferation in humans, compared with cats or monkeys, the number of branches of neuronal trees increases. Here again, in both the real and figurative sense of the expression, there is “terminal” addition of new branches. Ramón y Cajal’s well-known drawing, which compares the development of a pyramidal cell during vertebrate phylogeny and human ontogeny, clearly illustrates this point (Figure 78).

From the higher vertebrates to man, and particularly from the monkey to man, more and more synapses are produced during development, thus increasing the number of possible connections in the adult. With each wave of synaptogenesis, a number of excess connections form. Synapse redundancy amplifies cellular redundancy. Again, the pro-

longed production of some hormone or nerve growth factor could explain this ultimate stage of embryogenesis on the basis of a few mutations in communication genes (see Chapter 7).

This increase in cell and synapse redundancy, more marked in humans than in primitive mammals, is only temporary. As we saw in Chapter 7, cell death, synapse elimination, and selective stabilization help to give individual “singularities” to each neuron. But the stage of diversification is not fixed in the genes and, in this respect, differs from the transition of the nervous system of the worm to that of the sea slug. With each generation, interactions with the outside world regulate the elimination of this redundancy. The development of the brain becomes

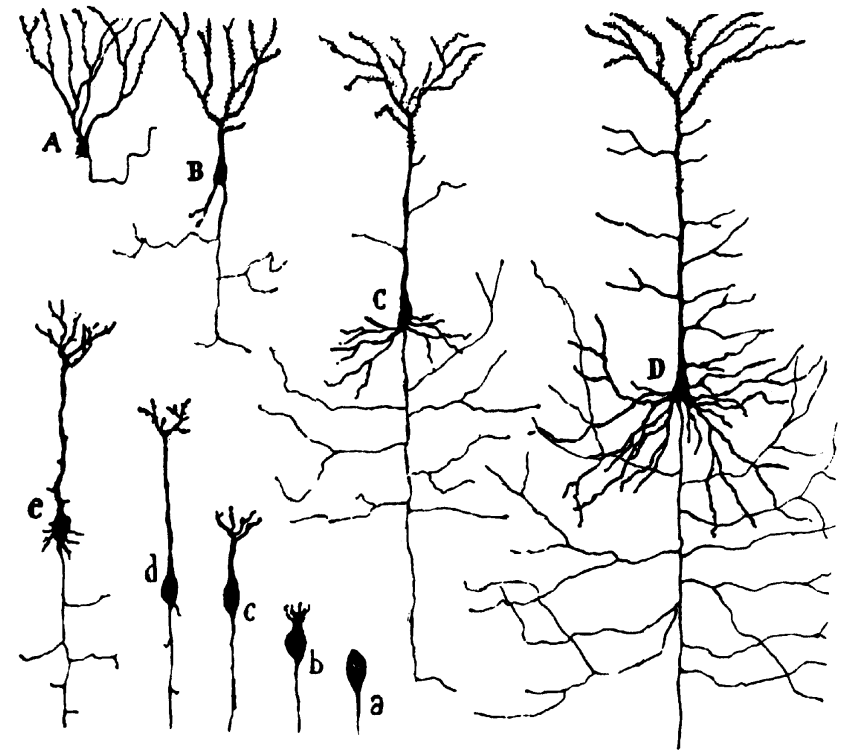


Figure 78. The phylogenetic and ontogenetic evolution of the pyramidal cell. The *top* line shows the phylogenetic development through the history of different species: the frog (A), lizard (B), rat (C), and man (D). The *bottom* line represents, from *right to left*, ontogenetic development in the mouse embryo: embryonic neuron or neuroblast (a), beginning of the dendritic branching (b), elongation of the apical dendrite (c and d), growth of basal dendrites and collateral branches (e). (From S. Ramón y Cajal, 1909.)

