In the formula for the number of civilizations in the galaxy presented by Sagan in Ch. 1, there appeared the factor f_i, which represented the fraction of life-bearing planets with intelligence possessed of manipulative capabilities. The following chapter, by Michael Arbib, discusses a part of the problem associated with the evaluation of this factor. He is concerned with the stages of evolution upon the earth which lead to the higher animals and culminate with intelligence in man.

However, the term "intelligence" is a complex one which raises many questions. What does one mean by it? Can one be sure that one understands a natural phenomenon before the features of that phenomenon have been duplicated in the laboratory? One must also be concerned with the propagation of intelligence. When might a machine be considered intelligent? If a machine can be programmed to reproduce itself out of a carefully structured environment, it is probably not very intelligent, but if it is programmed to reproduce itself out of a wide variety of environments which are encountered in nature, then it must certainly have most of the attributes that we attribute to intelligence in human beings. Surely man is more than just such a machine. However, it is doubtful that man can fully understand himself until he is able to produce such machines. These are some of the questions raised by Arbib in his discussion of the evolution of intelligence in the following chapter.

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The Likelihood of the Evolution of Communicating Intelligences on Other Planets

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The Story so Far

The series of papers compiled in this text focuses on three questions: First, are there "intelligences" elsewhere in the universe? Second, if there are, can we, at least in principle, communicate with them? Third, if such communication is possible, how might we implement it? In the first paper, Carl Sagan proposes that our search for intelligence focus on the possibility of a planet-based life made up of large complex molecules. Cameron, in the second paper, suggests that most stars probably do have planets, and Ponnamperuma, in the third paper, states that it is almost inevitable that if the orbit of a primitive planet lies in a suitable temperature range, then organic chemicals, "the building blocks of life," will form. When we convince ourselves that intelligences can evolve on other planets, we will have found a lower bound to the evolution of intelligence in the universe, because strange life forms may even drift among the stars—as those who have read Hoyle's *Black Cloud* may well imagine.

We shall also be interested in determining whether an intelligence that evolves is likely to create a technology, because it is probable that technology is required for interstellar communication. Although we evolved biologically to communicate using sound waves, it is conceivable that another species could have evolved means of electromagnetic communication.

Our task in this chapter is to understand to what extent one might expect intelligence to evolve, and to that end we must consider what we mean by "intelligence" and what we mean by "evolution." Some years ago a book appeared with the title, *Is There Intelligent Life on Earth?*. We shall assume that the answer is yes and use the evolution of the human brain as a paradigm for the way intelligence might have evolved. However, it must be stressed that much of the discussion will be in a realm far removed from the careful results described in the two previous chapters. It is one thing to simulate the motion of thousands of particles on a computer and see that they form into a disk which breaks up into a configuration akin to a star and several planets, or to pass ultraviolet light through a nearly empty jar and see that after a while some simple organic chemicals form. It is a vastly different thing—and inconceivable with present technology—to do the equivalent of taking a jar and energizing it for a few billion years to see if eventually intelligent life will be produced. At best, then, this chapter will attempt to make it plausible that, given that few billion years, it is almost inevitable that some sort of intelligence will evolve on any planet on which autocatalytic reactions have arisen. But whether that intelligence is anything at all like that of humans will be a very open question, and our attempts at an answer will at times be closer to science fiction than to science.

Evolution

The notion that life *evolved* on earth rests on the hypothesis that our planet initially had little in the way of chemical complexity, and by gradual changes, all of which are completely explicable by physical law, the complex organisms that we find on earth today have arisen.

There are two basic ingredients in the current theory of the evolution of life on earth. Darwin gave us the concept of natural selection—that organisms could be "selected" *naturally* for survival. For example, animals that were more fit in some way to live in certain environments would tend to reproduce more than other animals in that environment so that over the passage of time the animals that existed would be more and more adapted to the "ecological niche." The *ecological niche* is the complex of circumstances which provide the life space for a particular species. We should note that the ecological niche is not specified simply by temperature and climate, but also by what other organisms, plant or animal, live in the area, because as soon as a new type of organism evolves, there is then the possibility of evolving yet another species to live in the interstices and to exploit the new living relations thus made possible. Thus we have a proliferation of complexity of organisms with time.

The other ingredient in the theory of biological evolution is Mendel's idea of the *gene*. In modern terminology we would speak of the genes as forming the program which directed the growth of the organism from a single cell in interaction with the environment. If an animal lived long enough to reproduce, then portions of its genes would provide the program for the growth of its descendants. Note that this says that it is not any peculiarities the animal may have acquired in its lifetime that survive, but rather the "program" which survives. If an animal had acquired a long neck by stretching to nibble at trees, it could not pass that on to its child. However, if a change in the program (a mutation in its genes) gave it the character of being more likely to grow a long neck in a certain range of environments, then one could expect the offspring to also have a long neck. We thus have the distinction between the *genotype*—the type of growth program—and the *phenotype*—the type of the actual grown organism, which results from both the genotype and the environment in which it operates. The phenotype determines whether or not the creature will live to reproduction age and pass its genes on, but the actual changes from generation to generation are within the genes.

In the preceding chapter we are reminded that life on earth is built up from very simple building blocks. DNA, which we now believe to be the material from which genes are made, has only four or five "letters" in which the "programs" are written to direct the growth of organisms, while the actual building from these programs is done with amino acids, only twenty in number. It was suggested from this evidence that life came from a single precursor, but we must be a little wary in accepting this assumption, since the fact that only one type of basis "won" out does not mean that there weren't other "candidates" initially. Thus life forms on planets of other stars might be quite different even in this basic structure, though there may be chemical reasons to expect DNA to be ubiquitous. It might also be asked whether it is necessary for *any* (nonterrestrial) life form to have a genotype distinct from a phenotype, in other words, whether we have to have a program to direct growth and change, or whether in fact the organism might be able to reproduce itself as a whole. One might imagine some planet in a distant galaxy whose beings reproduce by xerography with no gene required! For some mildly convincing arguments in favor of the gene concept, see the section entitled, "What is the Role of Descriptions?" in Arbib [1969a]. When we try to extrapolate from the careful science of what exists on the earth, we get into the realm of science fiction so that the speculations in a book like Jose Farmer's *Strange Relations*, which explores some of the more bizarre forms that symbiosis and sexuality might take on other planets, may be as right—or as wrong—as those of the scientist.

Why Not Be a Rock?

At this stage, we should ponder the crucial question that evolutionists so rarely ask. It is so common to fantasize that evolution is a process existing for the sole purpose of producing human beings—that amoebae have been struggling out of the slime for millions of years trying to aggregate into human brains—that people never ask the naive question, "Why not be a rock?" If sheer survival and long life is the goal, what is superior to a rock? A rock has no problems, and even if, at the end of billions of years, a convict comes along with a sledge hammer and smashes the rock, at least it has a billion years of just sitting, which far transcends the human three score years and ten! So why aren't we all rocks? Unfortunately, earthly chemicals took a "wrong turn" a few billion years ago, along the lines suggested in the preceding chapter. Once some moderately complex chemicals form, it is likely that they will form aggregates that are autocatalytic: reactions occur in which a chemical triggers the production of more chemicals like itself. Once that epochal "mistake" was made, there was no turning back. It was not that all these chemicals were striving to be Man; there was no mystical goal or final cause which was "pushing them on." Rather, once there existed complex chemicals which were able to produce chemicals like themselves, there was always a probability that the resultant chemicals would be changed somewhat. There was then a small chance that a compound would arise that could produce more copies of itself than the older ones could. The whole of evolution was at that stage unleashed, and it is interesting to see to what extent life as we know it must then result.

Life as we know it is based on cells. This seems to make sense because a membrane surrounding chemicals in reaction can exclude some chemicals, while containing precious enzymes that can speed up the reactions. Again, a plausible case might be made for the emergence of DNA or some sort of general message to direct things. Hence there are plausible reasons for suspecting that, in the long run, any planetary form of life starting from autocatalytic reactions would eventually come to be—at least crudely—a multicellular form such as we know on earth. However, before we trace the development of a series of earth organisms which will give us some idea of the complexities that cells can enter into in their relations with each other as they move from single-celled animals to the intelligence of man, let us briefly talk about self-reproducing machines.

Self-reproducing Machines

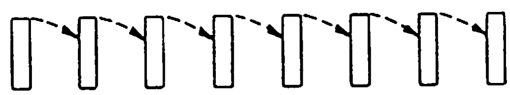
There are two reasons for briefly discussing self-reproducing machines here: one is that they will give us some insight into the processes of reproduction and evolution as physical processes: the other is that self-reproducing machines may well play an important role in interstellar communication.

As students of Southeast Asian politics know, it is widely believed that it is very simple to produce a self-reproducing machine of the type shown in Fig. 4.1. If the environment does indeed consist of a string of dominoes, and the system to be reproduced is a falling domino, reproduction can clearly take place. However, from our point of view this model is only at the level of simple chemical reactions that, once started, can continue to maintain themselves. What we are really interested in is whether really complicated systems can reproduce themselves in a way that we can understand on the basis of our physics and mathematics without introducing some mysterious distinction between living and nonliving forms.

Von Neumann [1951] noted that when we look at biological reproduction, the offspring that is produced is at least as complicated as the parent, but when we think about production lines, with machines producing other machines, we tend to expect a degradation of complexity. It is thus of great interest that Von Neumann was able to show that one could, in fact, have machines of arbitrary complexity which would reproduce themselves. We shall not go into the details here, but we can at least examine two figures which give an idea of the strategy, while omitting the detailed program.

With much careful programming one can specify the "universal constructor" *A* of Fig. 4.2, which when given a program I_N for constructing any other machine, *N*, will read through that program, compute upon it, piece together components from its environment, and construct a copy of the machine *N*, as shown in the right-hand side of Fig. 4.2.

Figure 4.1 A simple self-reproducing machine.



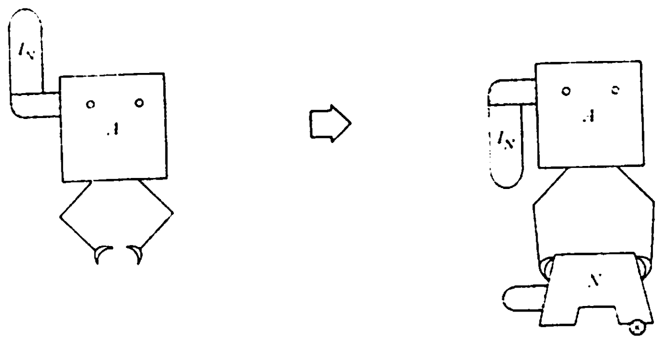


Figure 4.2 The "universal constructor" A, when given a program I_X for constructing any other machine X, A will read through that program, compute upon it, piece together components from its environment, and construct a copy of the machine X, as shown in the right half of this figure.

The procedure is somewhat unbiological—it is as if a mother, instead of starting with a single fertilized cell and growing it in her womb for nine months, were instead to start by piecing together the toenail and give birth to the child as the last hair was put in place on its head. There is now active research into how we might make "biological perturbations" of this theory, but here let us ask how we might modify A to obtain a machine capable of reproducing itself. One might think that the strategy would be to give A a description of A. Then A would compute upon I_A to yield as the X of Fig. 4.2, a copy of A itself. However, A equipped with a program has reproduced A without a program, so that it has produced a "jackass" as offspring rather than reproducing the initial configuration. The resolution comes from noting that in biological systems, a cell, before reproducing itself, will copy the genetic message, so that when it splits in two, one copy can go to each daughter cell.

These considerations yield the self-reproducing automaton of Fig. 4.3, in which A is augmented by two new subsystems B and C. When activity is initiated, the first subsystem to work is B, which makes a copy of the program I_D and inserts it in the holder at the top of B and C (see Fig. 4.3(*a*) and (*b*)). Then B transfers control to our universal constructor A which works through the program I_D. If we choose the described machine D to be in fact the machine $A - B - C$ without programs, then A builds the connection of A, B, and C (Fig. 4.3(*b*) and (*c*)). Having completed its construction, A transfers control to C which now takes the spare copy of the program I_D and transfers it to the "offspring" (Fig. 4.3(*c*) and (*d*)) and self-reproduction is complete.

Rather than go into details of this theory (for which, see Von Neumann

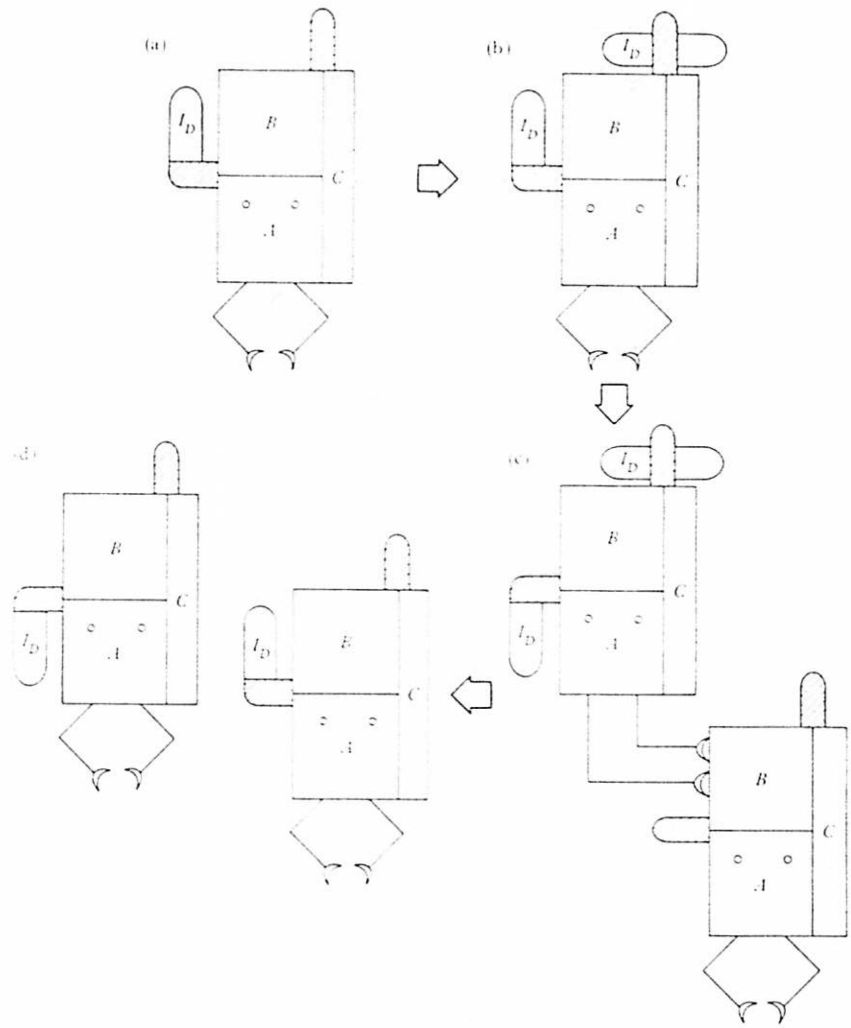


Figure 4.3 Self-reproducing automaton in which A is augmented by two new subsystems B and C.

[1966] or Arbib [1969], Ch. 10), let us devote the rest of this section to some speculation about the role self-reproducing machines might play in interstellar communication. Developments in artificial intelligence (for example, as discussed by McCarthy in Ch. 5) raise the question of the extent to which our eventual interstellar communication will be directly with living creatures, and the extent to which it will be with man-machine symbioses or even with a purely machine intelligence alone. In any case, much of the discussion of interstellar communication posits radio communication as the basic medium. However, we might well imagine trying to design a self-reproducing machine that carries out its own synthesis starting from the interstellar gas. These machines could then reproduce every time they travel a constant distance out from the home planet to yield a sphere moving out from the home planet with a constant density of these self-reproducing machines. Before leaving this line of speculation, we might ask: What if they start to mutate? Will it matter? Are we so lonely here on the planet Earth that we want to talk to anybody from out there, or must we be assured that we are getting accurate messages from another culture?

Intelligence

We now have some idea of the mechanism of evolution, which involves creatures reproducing and mutations (and other effects) changing the essential program for their growth, so that over time, certain types of programs become more common than other programs in a given ecological niche. What then is the "intelligence" that overly romantic writers have viewed as the goal of earthly evolution? For one thing, intelligence is not a single thing, and the present controversy on IQ tests reminds us that intelligence has many dimensions. It may well be, then, that on planets of other suns, many of the dimensions of intelligence will be different from those we know. However, we can isolate some essential characteristics of intelligence which may provide the substrate on which specific talents like musical intelligence, mathematical intelligence, plain horse sense, and so on can be erected.

To understand the characteristics of intelligence, we should consider that the processes of evolution yield creatures who in some sense model their world better and better, or at least those aspects of the world relevant to survival in some ecological niche. An organism is impinged upon by the world around it and carries out actions upon its world. It survives to the extent that its actions are appropriate to the world in which it lives. If an amoeba were to always extend itself into acid and away from food, there would not be any amoebae left. Thus to some extent even an amoeba can be viewed as a representation or "model" of the fact that acid is dangerous, and certain chemicals correspond to food. As we come to more and more sophisticated organisms (see the following section) we find more and more aspects of the environment are "captured" in the repertoire of behavior of the organism.

In this vein we might say that what characterized human intelligence is that instead of having a single "model of the world" wired in genetically so that all we can do is live in a limited environment and react in a stereotyped way, we are able to learn as we grow, to find out more and more about our world, to adapt ourselves to differing environments, and to learn skills that we can transfer to situations where we have never used them before. It appears, then, that the evolution of intelligence is a natural consequence of the evolution of living forms—as organisms evolve that are better adapted to react to the flux of the environment about them, so may we expect the occurrence of organisms able to recall things about their environment and to make plans and strategies on the basis of which they can act.

It is thus not implausible (though this discussion has done scant justice to all the subtleties) that once evolution "gets going" in biological systems, the evolution of intelligent organisms is pretty much inevitable, given enough time. Intelligence involves the ability to hypothesize, to try different things out, and to choose between alternative futures.

One of the interesting facts about the earth, which gives us some hope for thinking there may be more in common between intelligences in the planets of different stars than a quick browse through science fiction in its less anthropomorphic forms might suggest, is that on the earth visual systems have evolved independently in quite different species (see Gregory [1966]). There exist two general types of eye, the compound eye of the insect and the simple eye, with its single lens focusing light upon a whole array of cells, that we see in man. The "simple" eye occurs also in the squid and the octopus, even though they have evolved in completely different ways from man. Thus the fact that completely different paths of evolution—though admittedly they all occur on the planet Earth—have led to the evolution of similar structures suggests that there may well be many commonalities between creatures who have evolved to live on a planet illuminated by electromagnetic radiation—especially among creatures who must move around when subject to gravity. As we come to understand evolutionary theory better, we may actually be able to predict such commonalities. However, the gross similarities of visual systems should not blind us to crucial differences of detail (as we shall see below), and the diverse forms among terrestrial insects alone should remind us that vast differences will remain which can seriously hinder types of communication.

From Amoeba to Man[1]

Let us now give a short overview of the evolution of human intelligence. To start with, we indicate in Fig. 4.4 the basic organization of the computing system which underlies all multicellular organisms. Receptors take light, sound, and touch energy from the environment and convert it into electrical pulses which can propagate down various signalling lines to impinge upon various neurons. These neurons have already been changed

[1] This section has drawn heavily upon the works of Buchsbaum [1948] and Elliott [1969]. The reader is warmly recommended to turn to these two excellently written volumes to supplement our somewhat sketchy account. See also Altman [1966] and Herrick [1926].

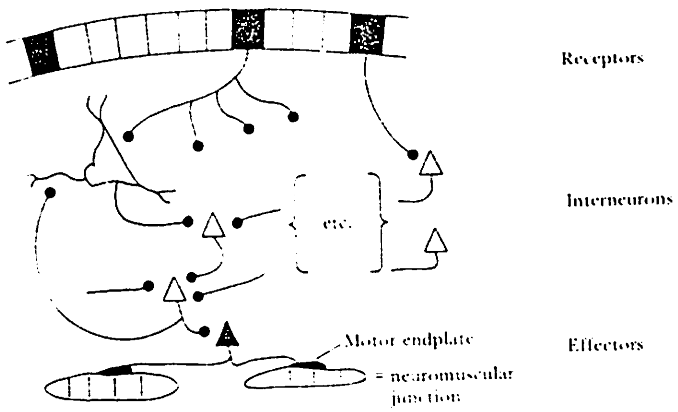


Figure 4.4 The basic organization of the computing system which underlies all multicellular organisms

by previous activity, and so they react on the basis both of what is coming in and the current internal state of the system. The activity of various neurons inside the net will then impinge upon muscles or glands, and so change the way in which the organism acts. We shall study forms of life that exist on the earth today to get some insight into how this sort of computation structure, which is at the root of intelligence as we know it, could evolve.

Our brains contain approximately 100 billion neurons, in addition to all the other cells that make up our bodies, so that our intelligence results from the orchestration of the interrelated activity of billions upon billions upon billions of single-celled creatures. Yet the single-celled amoeba lives today and is a very successful animal that can do very well as long as it finds food to live on. An amoeba can respond to the chemical gradients set up by a piece of food by extending pseudopods to surround the piece of food, closing upon it, and digesting it. It has the basic reactivity to avoid harmful chemicals and move towards chemicals that signal food. In its own ecological niche it does as well as man in his. (Man has a far broader and more varied ecological niche, and that is where intelligence enters.)

However, the amoeba is limited in that if bits of food were near two parts of the amoeba at the same time, it would try to extend toward both of them. The obvious "engineering improvement" is to provide the organism with the ability to coordinate its different parts.

A paramecium, which is still only a single-celled organism (remember that humans contain billions of cells) is already rather sophisticated. It is surrounded by little hairs called cilia. Whereas in humans each hair comes from a separate cell of its own, cilia are outgrowths of the single cell. These cilia can beat together to move the paramecium about, and in fact there exist microscopic filaments that connect the roots of the various cilia to yield coordinated movement. If the filaments are cut, the cilia wave in an even sillier fashion. Again, while the amoeba will ingest food wherever it makes contact, the paramecium has a distinct oral groove lined with cilia which can beat together to propel bits of food down the groove. Here we have a *highly evolved* creature which has been evolving as long as we have to live in a simple environment in which, because of its coordinated action, it can make a somewhat better living than amoebae do. In fact, a paramecium exhibits a rudimentary memory in that if it bumps into an obstacle it can compensate: it backs off, turns a little bit, and goes forward again, and if it bumps into something, it repeats the routine, it backs, turns a little bit, and goes forward again. Thus it has a little bit of memory: it can remember whether something it did failed, and do something else. Of course, it isn't sophisticated enough to know that if it has gone round through 360°, it has had it; it will just keep turning round and round until it dies.

Although we have been discussing creatures that exist today, we are perhaps recapitulating some of the development that must have occurred in that branch of evolution which led to man. In the amoeba, we see the basic ability to respond to the crudest stimuli, both nutritious and noxious. The paramecium further exhibits coordination—the organism can begin to act as a whole—and has a rudimentary memory in that what it does now depends somewhat on what it has just done. However, this is a far cry from the human ability to build on a lifetime of experience. To gain more insight we must turn to the sponge, the simplest of all living multicellular creatures.

With hindsight, we can see good reasons for the evolution of cellular organisms. Of course, the first colonies of cells did not know that they were forming multicellular organisms; it just happened that such groupings tended to survive because at the time they were able to exploit the environment a little bit better than their contemporary single-celled organisms could do. Sponges comprise a colony of cells, each somewhat like little paramecia, but which are embedded together in a single matrix, where they cooperate to the extent that their cilia bear together to force a continuous stream of water that goes in through little incurrent pores and out through a large excurrent opening. The various cells, instead of moving individually at random to occasionally encounter food, together create a current that is likely to bring food to them all. However, despite this cooperation to "encourage" food to move in their direction, there is little real coordination; there is no nervous system that links all the different parts together. If something noxious bumps into one of the pores, then the cells around the pore can contract to stop that noxious thing from getting inside the sponge, but there are no paths to enable related action elsewhere in the organism—the sponge is like a multicellular amoeba, in that it can only react locally.

The hydra is the simplest multicellular organism with "global coordination." It lives in fresh water ponds with its base moored on a rock, and it has little tentacles with which it can grab little things as they come by and stuff them into its gut. However, the important point is that it has a nervous system, albeit a diffuse and rudimentary one, which allows the effects of a stimulus to pass through the whole organism so that the whole organism can bend away from a noxious stimulus. In other words, the whole organism can begin to act in a coordinated way. However, there is little detailed computation: if you "hit" it hard enough, more of it will get out of the way, but there is no wherewithal to decide what is the appropriate action, or how to pool different stimuli.

In the flatworm we at last find a nervous system which does more than just carry a shock further and further away from the point of stimulation: it can also combine different types of stimuli. The flatworm does not have pattern-sensitive eyes, but rather photo-sensitive cups, which these animals can use to detect which side is brighter, so that it can move away from light by signaling a contraction to the muscles on the side of the body away from the light. Its nervous system has a great deal of structure to it and can carry signals in an orderly manner down the two sides of the animal. We also see the beginnings of a brain—the flatworm has a head end with a greater amount of computation, not very much, but just sufficient to take account not only of information about chemicals and touch, but to pool it with the primitive visual information that comes in from the photo-sensitive spots. The nervous system is sufficiently sophisticated that if the animal is moving along a stream and feels the pressure from the stones underneath, smells rotting meat, and is exposed to a light from the same side, it can pool all the effects to compute which way it will turn. Here we see all the ingredients of the real nervous system as we know it.

We close this section by briefly noting the two major differences between the nervous systems of flatworm and man. The first resulted from the evolution of more and more sophisticated types of *vertebrate* organization, so that we have a single spinal system which can relay information from all over the body to the head end where it can be pooled and processed by the brain. Thus the organism becomes a coordinated system which acts much more as a whole than the invertebrates which comprise, to some extent, a collection of subbrains, each controlling a separate portion of the animal with relatively slight constraints as to how it acts overall. The second resulted from the evolution of the *mammals*, where the keeping of the embryo in a womb where metabolic conditions could be kept more constant until it was born was coupled with the evolution of a new outgrowth of brain called neocortex, which gets bigger and bigger until in man the huge outfolding of neocortex covers all the "older" brain structures. It is the neocortex which seems to contribute most to our ability to remember as we do, to plan, and to use speech.

Cultural Evolution

With language, man acquired the substrate for culture, for it allowed the fruits of intelligence to be pooled and shared with the other members of the species without using the slow genetic route. Today, cultural evolution seems to dominate the biological processes discussed previously. Men —or at least man-like species, the hominids—have changed immensely in the last million years. They evolved the upright gait which has freed their hands for the delicate manipulation which has allowed them to exploit tools; since the hands are free, it is unnecessary for them to fight with their mouths as many animals do, and the mouth has been freed for the subsidiary evolution of the vocal apparatus.

It is hard to predict whether man's biological evolution will continue. We can make suggestions about what sort of social organizations may be needed to stop the crises that come from war, overpopulation, and so on, involving greater levels of social awareness and coordination. It would be pleasant to think that there might be some biological mutations that would make man a more genuinely social creature and remove certain aspects such as aggression, which may have been useful for primitive hunting tribes but are not for modern society. But we can't predict that this will actually happen. We have stressed that evolution is built on local adaptations for better exploitation of an ecological niche, and must not be regarded as a giant progression whose goal is man. In particular, there is no guarantee that any future biological evolution would bring us closer to a more enlightened society. However, though biological evolution has no single goal, we can impose goals, and the hope is that we are now conscious enough that we don't have to be bound by just the chance interactions of different species in an ecological niche, but can begin to decide what things we would like to be important in order that we can create goals, and then we can begin to structure our society to achieve them.

In the historical development of man, we see less of the biological operation of natural selection changing physical structure and more and more of the building up of symbol systems that can be shared. No longer are the "messages" encoded in the genes to be passed on only from parents to child. Today our evolution seems to center more on the evolution of scientific systems, systems of different professions, systems of entertainment, systems of culture and religion, and so on, that can be passed from person to person by such mechanisms of nongenetic transmission as education. Again, technology has enabled us to increase the range of environments in which we can survive. This widening of the ecological niche is one of the most notable achievements of mankind. But while man is physically similar in many niches, we see dramatic differences in culture. Bees also have a culture, a social system, where each organism has a part in an overall scheme, but human culture is different in that having language, we have some overview of our culture. Even if we cannot understand everything about society, we can at least try to make some sort of judgment about it and try to describe to others at least the outline of what is happening, even if we cannot master many details. Might we, then, be able to communicate something about our way of life, our society, and our science, though, to the creatures of other planets? To succeed, they must have evolved to the stage in which their model of their world (see the preceding discussion) is based upon nongenetic transmission, for if the only way they can receive information from other creatures is by being born as their offspring, we have little chance of talking to the people of Betelgeuse!

In teaching someone to drive, linguistic instructions let you put a person into a car, and as long as you are in a fairly quiet street, you are able to give him the necessary instructions. On the other hand, you are not going to let him go into peak-hour traffic until he has added to that knowledge a great deal of refined motor coordination that involved brain structures of much older evolutionary origin. Language can get the person into the right "ballpark," while older systems can refine these activities to a level of skill. Together these play a crucial role. If you were driving across a piazza in Naples, you could not speak sufficiently fast to encode in a normal sentence the fact that there was a car coming at 45°, another car coming at 33 mph at 21°, and so on. You have to rely on older preverbal visual mechanisms that evolved beautifully to coordinate spatial patterns of sensory information with spatial patterns of action. Language evolved on "top" of that to get the right sort of "ballpark" of operation which gives people the basic idea of driving. Then they can use their "older apparatus" to refine the parameters and use special information efficiently.

Often, when we talk about language, we think so much of language as *the* human ability that we forget that the reason it works so well is that it exists on top of a substrate we share with other humans, which is not very easy to verbalize. Acknowledging this substrate emphasizes the problem of talking to creatures in a language that is universal, in the sense that if we give them sample programs, they will be able to compile our language into their own "machine language." Eventually, we may be able to communicate with them at some level, but the problem is to find how to express things in a "machine language" so simple that any technological civilization must be able to comprehend it.

What Can Be Communicated?

In terms of communicating with a far distant civilization, let us note that by "human intelligence" we do not mean the intelligence of any one particular human: what man knows is not what any human knows. When we communicate with a race on another planet, we will not be communicating with any one individual, but rather will be communicating with the whole species. In some sense because our communication is a message in linguistic form, it will presumably be something that a single individual could *comprehend* and could follow through—even if it was a 50-yr-long message. But the *creation* of the message will require a distillation which no single individual could devise. The difference becomes clear when we note that it is much easier to read a book than write a book—and there are many, many subjects in which one could read and comprehend a well-written book, but this is quite different from being able to write a comprehensible book in that area. Given that the message will in some sense be the distillation of the species' knowledge, it will presumably involve a huge amount of correlating techniques, assessment of intelligibility (which could require computer-run surveys), and so forth. It may well take so much technological input in addition to the contribution of individual experiences to complete it, that no individual will fully comprehend why that particular message is the best we can send, though many individuals will be able to comprehend that it seems to be a good message. Sending the message is not a matter of phoning up Charles X who will be on a planet near Syrius and having a chat with him about the latest ballgame results. Presumably the message is going to be some sort of encyclopedia, a distillation of much information. Given the evolution of our own intellectual processes, it would seem necessary to correlate beyond the level of just having individual articles written by individual specialists—the message will have an immense computer input, and humans will also be hooked into it. Yet the end product *will* be human.

What can we expect to communicate to beings who have evolved nongenetic ways of transmitting information about their environment? In the first chapter, Carl Sagan observed that if there is to be any chance of our contacting an extraterrestrial culture, that culture must have evolved a stable form of organization, having passed the stage of risking annihilation by playing with atomic weapons. Given such stability, we might expect the culture to last very long indeed and so might guess—and it is a completely wild guess without any foundation—that the average stable civilization is 10^6 years old. This guess is somewhat disturbing more subjective states may well have value—the very strangeness of an alien viewpoint may make us see new things, just as great poetry may succeed not so much because the poet conveys an explicit situation, but because the reader finds in the poem "chords" that change his perceptions.

What, then, can we hope to communicate with any "technological" species? It appears that purely symbolic constructs which can be reduced to a postulational system, for example, mathematics (which might include much of physics as well as even basic rules of social organization), can be communicated. Surely a preliminary phase of communicating simple axioms to educate the alien intelligence and let them educate us in basic concepts is first required. However, it seems unlikely that we could share ideas which involve affect and emotions; for example, we would be unable to communicate the feel rather than the abstract description of perceiving something.

Effective communication would require mutual education and adaptation here as elsewhere. Consider again the problem of communicating about vision with a blind person. You could convey certain mathematical descriptions involving wavelengths and also the fact that there are surfaces with different absorption coefficients, and then you could get across the idea of sensors which can use these differences to get information about distant objects which would prove helpful in navigation. But this is far different from conveying the glory of a sunset. As we have seen, even creatures which share the possession of visual systems may process their sensory inputs in radically different ways. Even though one might claim that the human brain is a universal computer—in the sense that it can achieve anything at an intellectual level given enough time—the fact remains that the difference in organization of our perceptual systems from those of other species may be such that there are certain things that are immediately comprehensible to us, but which would not be at all immediate to creatures in other civilizations.

This cautions us that even if we were to convey basic mathematical forms between the mathematicians of the two races by starting with the postulates, if the elementary components of the theory get their motivation from some sort of perception that is intricately tied to the way in which the brain which originated it has evolved in a particular type of environment, then no matter how much may be shared in the way of ability to manipulate the calculi of the system, it may still be extremely difficult to build up any sort of intuition.

Even though few of us can hope to convey fine nuances of emotion to our fellow humans in linguistic terms, we can convey much by way of empathy, because we have enough in common both in the way our brains are structured and in the type of society in which we have grown up. However, if an organism has evolved sufficiently differently, the dimensions may vary too much. You might be able to tell it some of your behavioral repertoire, but if its society is sufficiently different, it may be difficult to convey even that. Even on the planet Earth the same biological substrate of humanity has undergone much divergent cultural evolution. One finds that behavior which is considered as normal in one society—homosexuality, for example—disgusts people from other societies.

Our main hope for interstellar communication is based on the belief that a technological civilization must have numbers. It is hard to conceive of a psychology which could do technology without being able to count, and add, and multiply. To do the geometry necessary to describe the motion of its planets it must have some theory like conic sections or calculus. Thus one might expect such things to be in the repertoire of a scientist in any technological culture. Freudenthal has written a book which presents LINCOS, a language for interstellar communication. The strategy described is to start by sending messages that make clear that you are talking about numbers. You can then build towards calculus and coordinate geometry, on which basis you can start to discuss physics. One might expect (though Drake's ideas on neutron stars may suggest a counter-example) that Newton's laws hold anywhere as a reasonable first approximation, so that any scientist would eventually begin to recognize that you are talking about Newton's laws. After a while, you have a language in which you can describe the motion of particles, no matter what the senses of the creature are, or whether he perceives these motions by vision, by x-ray, touch, or another method. Just as in computers we build up higher and higher level "languages," so we may build up a higher level of language which approximates more the way we describe the world, even though we started from what we considered to be sufficiently basic physics that the alien scientist could understand. This way we can tie in more and more events to his perceptual systems, but this is still quite different from conveying the "feel." For example, the way a blind person perceives physical shapes is quite different from the way a sighted person does, and the idea of huge distances is somehow more abstract for someone who lacks a sense akin to vision.

Our emphasis on possession of technology rules out the model of a gorilla communicating with a man. The gorilla does not have language, and he does not have mathematics; it seems that we have to start at a higher level where we share at least the ability to use language. In particular, the ability to describe things that do not exist, to describe possible alternatives besides those that are actually perceived, is necessary. To build technology you have to be able to make hypotheses, to test hypotheses and, to a lesser extent, to look for unifying laws.

We need beings who can manipulate symbols in ways that are far more flexible than would result from simply going around the world taking snapshots. (Parenthetically, since we cannot assume that extraterrestrial beings will have a purely visual sense, we cannot guarantee that if you send out TV transmissions, the beings will eventually figure out how to project them on a TV screen, and then see them as we see them.) If you describe your geometry in terms of elementary number theory, then even if the being with whom you communicate can't perceive visual scenes, he certainly must have the idea of objects located in space and so can recognize a coordinate geometry description of those things. Even if he cannot really feel what you feel about certain constructs described, at least he can begin to understand your coordinatization, and he can then re-represent that in whatever is easiest for him. It might be that he will end up just putting it into a TV picture, because he does have a visual sense like ours. It might be that he will build plastic models and that people will feel them with certain senses, or some other method could be used. But the point is that you have got to have some sort of representation that is sufficiently universal that no matter what senses he has, if he can build a technology, he will have enough science to use that basic numerical representation.

Even though with our symbol systems we may be able to communicate all our mathematics, all our physics, perhaps even the basic rules of social organization, nonetheless, no matter how good interstellar communication may become, we may never know the full beauty of the x-radiation of a sunset for the inhabitants of a planet in the galaxy Andromeda.