WHAT IS AN INTELLIGENT MACHINE?

W. Ross Ashby
University of Illinois
Urbana, Illinois

Summary

From the "intelligent" processes we must first split off those that are peculiar to the living brain, but only because they are not commonly met with elsewhere. These processes are of interest but are neither intelligent nor stupid, neither good nor bad.

The "intelligent" processes par excellence are the goal-seeking--those that show high power of appropriate selection. Man and computer show their powers alike, by appropriate selection. But both are bounded by the fact that appropriate selection (to a degree better than chance) can be achieved only as a consequence of information received and processed.

Machines can be made as intelligent as we please, but both they and Man are bounded by the fact that their intelligence cannot exceed their powers of receiving and processing information.

1. Introduction

I am very pleased to have the privilege of addressing this conference today because I believe the time has come when we should notice a turning point in our views on the nature of brain and of brain-like mechanisms. The 1950's were largely a decade of ferment and progress. The 1960's, I believe, will be a decade of consolidation, of the establishment of a firm framework of ideas within which the whole science of brain-like mechanisms will move for quite a number of years to come.

The point is that until recently we all tended to assume that the capacities of the brain, especially of the human brain, were unlimited. We felt that if a man were clever enough he could do anything--the genius could solve any problem, I say that that belief must go. It is obstructing progress. In the 60's it will be recognized as being an ignorant and superstitious as the belief of the small boy who thinks that his big brother can lift anything. Today, we know what the word "brain-like" means, and we know what are a brain's limitations. We know, too, that these limitations are exactly the same for the human brain and for the machine because they are the limitations inherent in any system that behaves in an orderly and law-abiding way. The system that passes these limitations gets its results by pure magic. Before I go on, however, to treat these matters in more detail, I would like to discuss some minor matters so that we can get them out of the way.

Brain-like processes can be clearly divided into two classes, according to whether the process is goal-seeking or not. It is the goal-seeking processes that are par excellence the intelligent ones, whether they occur in a machine or a brain. But there are also a number of processes that occur in the brain that are not goal-seeking. Let me deal with them first.

The living brain has, of course, a great number of interesting properties that are of interest simply because they do not occur commonly elsewhere. The brain, for instance, has some unique biochemical processes; and it has interesting electrochemical processes. Of special interest to the computing engineer are the special network properties that it has developed, and the stochastic properties that it has developed for special purposes. The chief point about these nongoal-seeking processes is that they are neither good nor bad in themselves--they are simply processes that the laws of nature provide--like oxidation--and the brain, under the guidance of natural selection and evolution, develops or suppresses them in accordance with whether they are useful or harmful. They are brain-like only in the sense that they are seldom seen outside the brain. They can all be simulated on computers because they are straightforward natural processes.

In considering these brain-like processes, we should remember that the computer is actually superior to the brain, because the computer can be made to behave as if it were totally devoid of any operational structure. As a result, the computer can, in principle, carry out any well defined process. The living brain, however, has been so molded by five billion years of evolution that it is now very highly specialized to match the needs of this terrestrial environment. This environment, we are beginning to realize, is nothing like so general as one is apt to think it. Its distribution in space, with a three-dimensional Euclidian metric, the extraordinary commonness of continuity in it, its tendency for effects to be much localized, and the tendency for the same properties to turn up again and again in different places, all these features are highly characteristic of the terrestrial environment. For them to occur in the computer, they would have to be programmed in with great labor. Because the living brain has faced this very special environment for so long, the brain
has become equally specialized in its operational methods. As a result, the brain, far from being a remarkably flexible mechanism, is now appreciated as a system of remarkable inflexibility.

Of these brain-like processes, other than the goal-seeking, I wish to say little here, but before I leave the topic I would like to say that I think the most promising line of research at the present time is the study of systems with large numbers of equilibria. Our knowledge of such systems is extraordinarily small. A great deal is known about the statistical mechanics of large physical (i.e., Newtonian) systems, but these usually have very few states of equilib­rium. The simplest example of a system with a really large number of states of equilibrium is a dish of sand, in which the particles will rest in a great number of different configurations. But the only activity of this system is the tiny movement of the grain of sand as it moves from a nonequilibrium to an equilibrium—a movement too small to be interesting. What we need to know more about is the system that has a very great number of states of equilibrium and, sufficient dynamism so that its trajectories, before it reaches a state of equilibrium, are sufficiently long and complex to be interesting. I have shown elsewhere how such systems tend to show something of living organisms, and I have little doubt that much more remains to be discovered. Here, of course, we recognize that a system with thresholds, such as is the nervous system is just such a system with a great number of states of equilibrium. It seems to me to be almost incredible that having known for fifty years that the nervous system works largely on threshold, we should, in the 1960's, know practically nothing about how such a system tends to behave when the system is large enough for it to show something of its statistical mechanics.

So much then, for those properties that the brain possesses, but that are essentially ordinary as natural processes, I now come to the other brain processes—those that are universally recognized as somewhat extraordinary. They are—the goal-seeking.

2. What Is "Intelligent"?

Until a few years ago there could have been a considerable dispute about what was meant by an "intelligent machine", but that time is past. The position was clarified some years ago, and has been known long enough for any refutation to have come forward. No refutation has been of­fered. Not a single clear counter-example has been given in the last ten years to show that an intelligent system is anything other than one which achieves appropriate selection. This is the touchstone of intelligence. According to this view, intelligent is as intelligent does.

Let me give some examples to make clearer what I mean. If a man plays chess, we need not judge his powers by listening to his boasting—we simply observe whether the moves he makes are very highly selected out of the totality of legal moves, being selected from just those few moves that bring him rapidly nearer the win.

Again, the good workshop manager is one who, in spite of all the confusions and difficulties of the day, issues such carefully selected in­structions as will steer all the work through by the end of the day. Again, signal men show their intelligence by selecting just those pat­terns of operations in their box that gives, over long intervals of busy traffic, an accident number of zero. And in the so-called intelligence tests, which do test something of what we mean by intelligence, the operational cri­terion is simply "did the candidate select the right answers?"

Thus an intelligent machine can be defined as a system that utilizes information, and pro­cesses it with high efficiency, so as to achieve a high intensity of appropriate selection. If it is to show really high intelligence, it must process a really large quantity of information, and the efficiency should be really high.

In biological processes, appropriate selection and intelligence is shown essentially by regulation; the living organism, when it acts "intelligently," acts so as to keep itself alive. It acts, in other words, so as to keep the essential variables on which its existence depends within physiological limits. This is a straightforward act of appropriate selection, and the animals, as they ascend the scale of intelligence, show their ascent precisely by their power of regulating their environment in spite of greater ranges of stresses coming to them. In Man, the primary goals are what evolution and natural selection have built into him. The other goals are all secondary, developed either as species characteristics or by learning.

This approach to the nature of intelligence gives us an angle on the subject quite different from the older philosophers', and one which at a stroke ties it firmly to the modern theory of information. For "regulation" simply means that in spite of many threatened deviations from the optimum, the organism so behaves that the devia­tion does not occur; that is to say, the correct form is maintained. This achieving of a correct final form, repeatedly in spite of a stream of disturbances, is clearly homologous with the correction of noise by a correction channel. The noise threatens to drive the form or message from its desired shape and the correction channel so acts as to bring it back to the true form. A natural measure of the degree of intelligence can thus be given in the terms of Shannon's theory of communication, and with it not merely a measure
but a complete grasp of the logic of the situation and of what is implied.

3. The Limit to Intelligence

As soon as we recognize that an intelligent system, whether living or mechanical, is simply one that behaves in an intelligent way, we appreciate that the test of intelligence is the power of appropriate selection. All intelligent actions are actions of appropriate selection.

As a result every intelligent system is subject to the following postulate:

Any system that achieves appropriate selection (to a degree better than chance) does so as a consequence of information received.

One would imagine this postulate to be completely obvious were it not for the fact that many discussions about the powers of living brains subtly and tacitly deny it. Yet what would happen if the postulate did not hold? We would have the case of the examination candidate who starts to give the appropriate answer before the particular question has been given! We would have the case of the man who submits an accurate insurance claim for damage by fire before the fire has broken out! We would have the case of the machine put on the market for which the manufacturerWestern computer in order to enable the computer to carry through the same process and to arrive at the same answer. The point is, of course, that when it comes to things like three-dimensional geometry, the human being has within himself an enormous quantity of information obtained by a form of preprogramming. Before he picked up his

Science knows nothing of these things. What will happen in the future we can't say; but it is quite clear that in the middle of the 20th century we must reject such possibilities and proceed on the assumption that they do not occur.

The moment we say such events do not occur we are implicitly saying that all systems whether human or mechanical are subject to this postulate—they can achieve appropriate selection only if they receive and process the appropriate amount of information.

This point of view at once brings them under a quantitative limitation. For appropriate selection is fundamentally homologous, as I said, with the correction of noise, and therefore the amount of correction that can be applied is subject to Shannon's tenth theorem. Though the theorem has a somewhat different aim, it says that if a certain quantity of error is to be removed from the final form (that is to say, a certain degree of appropriate selection is to be made), then at least that quantity of information must be carried along the correction channel. When a human being undertakes such activities of correction, or of regulation, or of appropriate selection, he is acting as the correction channel, and he cannot achieve this appropriate selection unless he receives and transmits the necessary quantity of information.

The same point can be made in a simpler and more primitive form, as I have done in the law of requisite variety, which shows that in the most obvious and common-sense way the processing of the necessary quantity of irrelephant must be done if appropriate selection is to be achieved by law, and not by mere magic.

Today then, we are in the position of being able to say of the human brain that it must work in one of two ways. Either it works subject to this postulate, in which case it achieves appropriate selection because it has received and processed the necessary amount of information, or it is behaving in an entirely magical way, producing correct effects without corresponding causes.

I do not say that it is impossible that the human brain should sometimes do wonderful things—I believe that the universe is still full of surprises; but what I do say is that those who maintain that the human brain is not subject to my postulate must accept the consequences of the alternative and must declare that the human brain sometimes achieves appropriate selection without receiving the necessary information. And it is obviously admirable that they should produce evidence to show that this remarkable event does actually occur. Until such evidence is produced, the postulate must stand.

It may perhaps be of interest to turn aside for the moment to glance at the reasons that may have led us to misunderstand the nature of human intelligence and cleverness. The point seems to be, as we can now see with the clearer quantitative grasp that we have today, that we tended grossly to mis-estimate the quantities of information that were used by computers and by people. When we program a computer, we have to write down every detail of the supplied information, and we are acutely aware of the quantity of information that must be made available to it. As a result, we tend to think that the quantity of information is extremely large; in fact, on any comparable scale of measurement it is quite small. The human mathematician, however, who solves a problem in three-dimensional geometry for instance, may do it very quickly and easily, and he may think that the amount of information that he has used is quite small. In fact, it is very large; and the measure of its largeness is precisely the amount of programming that would have to go into the computer in order to enable the computer to carry through the same process and to arrive at the same answer. The point is, of course, that when it comes to things like three-dimensional geometry, the human being has within himself an enormous quantity of information obtained by a form of preprogramming. Before he picked up his
From the collection of the Computer History Museum (www.computerhistory.org)

pencil, he already had behind him many years of childhood, in which he moved his arms and legs in three-dimensional space until he had learned a great deal about the intricacies of its metric. Then he spent years at school, learning formal Euclidian methods. He has done carpentry, and has learned how to make simple boxes and three-dimensional furniture. And behind him is five billion years of evolutionary molding all occurring in three-dimensional space; because it induced the survival of those organisms with an organization suited to three-dimensional space rather than to any other of the metrics that the cerebral cortex could hold, evolution has provided him with a cerebral organization that must be peculiarly suited to the manipulation of three-dimensional entities. So when a mathematician solves a problem in three-dimensional geometry, he tends grossly to underestimate the amount of information involved in the process.

When he does it in a computer, he tends grossly to overestimate it. What I am saying is that if the measure is applied to both on a similar basis it will be found that each, computer and living brain, can achieve appropriate selection precisely so far as it is allowed to by the quantity of information that it has received and processed.

Because of this hidden preprogramming of every human being, nothing is easier than for him to achieve results with extreme quickness, provided the question falls within his specialized range. But this is no more miraculous than the power of any other machine that is heavily preprogrammed to be quick. Most of the examples commonly given purporting to show some peculiar facility possessed by human beings are of problems in which human beings are peculiarly experienced, either personally or by the hereditary equipment that has come to them. Take for instance the playing of chess. The first thing that has to be explained to the boy of ten is that the rows, columns, and diagonals are significant. Because he is a human boy aged ten, long experienced in two-dimensional Euclidean geometry, we can indicate rows, columns, and diagonals to him by merely flicking a finger at the board.

The computer, however, being stripped down to an absolute zero of metrical properties, has to have the whole metric of the chessboard explained to it in detail, because it would just as readily play on a board with a metric that would seem crazy and quite impossibly difficult to a human being. Thus the fact that a human being is especially good at human problems is no more remarkable than that the digital computer is especially good at problems involving powers of two, or that the analog computer is especially good at handling continuous functions. I say that whenever a human being is found to be peculiarly good at a particular class of problems he will always be found to have had substantial preprogramming in those problems. The alternative is that he is getting the answers by magic.

4. What Is a "Genius"?

We can now consider briefly the question of the so-called "genius," and the question of his nature. There are two gross fallacies that infest our thinking about the genius.

The first is that after many scientists have tried to solve a problem, we imagine that the one who solves it must have some peculiar power. This is about as reasonable as letting 1024 people predict how a coin will fall ten times in succession, and then, when one person gets all ten right, trying to find the explanation of his phenomenal powers of prediction!

Isaac Newton, for instance, recorded when he was quite young that he always thought of everything as flowing into everything else; this was just his natural way of thinking and very congenial to him. He used this way of thinking on almost everything. Is it surprising that this was the man, who, at a time when the calculus was on the verge of being discovered, was actually the man who got it first? Compare him with, say, Planck, at the beginning of this century, when science was crying out for a man who could think of everything as going in small, discrete jumps. Had Newton been unlucky enough to have been born in 1900 he would have found himself peculiarly handicapped at the time when the quantum theory was just being formulated.

Clearly, the concept of a genius is apt to arise because after a number of workers have tried various ways of solving a problem, none of them knowing beforehand which is the right way, and one of them succeeds, we come along, pick this person out, and say he is remarkable. Now, part of the selection involved here was not made by that person; the selection is made by us, who pick out this person because of his performance. This very common mistake in statistical logic must be responsible for a substantial amount of our allocation of the title of 'genius'.

The second fallacy is the idea that the genius can go, as it were, straight to the answer without doing the work. In actual fact much of the work consists of making trials, which is, of course, a powerful way of gaining information. Many of the recognized geniuses are people who, by thinking about the subject day and night, are making trials of new combinations and new ways in great numbers. Take for instance the mathematician Gauss, who is doubtless generally accepted as an excellent example of a genius. Hear his own words about how he achieved a certain result, in a letter to Olbers: "Perhaps you remember my complaints about a theorem which had defied all my attempts. This lack has spoiled for me everything else that I found, and for four years a week has seldom passed when I would not have made one or another vain attempt to solve this problem—recently,
very lively again. But all brooding, all search­ing, has been in vain." Then he adds "Finally I succeeded a few days ago." And then he adds, "Nobody will have any idea of the long squeeze in which it placed me when I someday lecture on the topic." Undoubtedly, one of the reasons why a person is a genius is that he pays the price for it by sheer hard work. He processes the necessarily large quantity of information.

If the human brain is especially clever and slick at those problems for which it has been preprogrammed, we should find, of course, that it is peculiarly stupid and slow at those problems that are subtly contrary to the pre­programming. As far as I know, very little exploration has been done in this direction. We are not proud of our mistakes and it is only quite recently, almost within my lifetime, that psychologists have seriously paid attention to the defects of the ordinary human being instead of simply trying to exaggerate his abilities. But we do know that there are a certain number of events that show how he can be peculiarly handicapped. It is, of course, obvious that any species that tries to discuss its own sexual habits will always have difficulty, simply because the mixture of the real and the symbolic will always tend to create a confusion. We need not be surprised that we can discuss the sexual behavior of the stickleback with the utmost precision and objectivity, and then fall into a hopeless muddle when we try to talk about the sexual habits of the young man and woman of today. Other examples, are the well known dif­ficulties that occur when we try to make simul­taneous hand and foot movements in a way that do not match the age-old needs of gravitation and locomotion. Again, there are the demonstrations produced by Amos which show how strongly we are impelled to see relationships simply because we are preprogrammed to see them. There is one example, for instance, where one looks through a hole into a box and one sees apparently a toy chair suspended in mid air. Then one looks through a window in the side and one realizes that there are really a number of pieces scattered throughout the space but so arranged and strung on wires that when seen from one point they present the perspective of a chair. Then the observer, having seen beyond all question that the pieces are widely separated, goes back and looks through the hole again at the appearance. He cannot prevent himself from seeing one chair in one place.

5. There Is No "Real" Intelligence

Is there, then, no such thing as "real" intelligence? What I am saying is that if by "real" one means the intelligence that can perform great feats of appropriate selection without prior reception and processing of the equivalent quantity of information; then such "real" intelligence does not exist. It is a myth. It has come into existence in the same way that the idea of "real" magic comes to a child who sees conjuring tricks. At first the child believes in "real" magic. Later, after he has found how tricks are done he no longer believes in transcendental "real" magic; he replaces the myth by genuine knowledge of the processes of actual conjuring.

6. Consequences

What now are the consequences of this point of view? Especially for the computing engineer?

The first fact is that in talking about "intelligence," whether of the living brain or of the machine, we must give up talking about two sorts of intelligence. There is only one sort of intelligence. It is shown in essentially the same way whether the brain is living or mechanical. It shows itself by appropriate selection. It always implies the same underlying activity—that information in the required quantity is taken in (either immediately before the problem is given or at some time earlier as preprogramming) and that this quantity of information is processed with sufficient efficiency so that the total quantity does not fall below the point where it is no longer sufficient to allow the appropriate selection. The living brain has had only one problem throughout evolution: how to get the necessary information in, and how to process it with reasonable efficiency. The problem of today's computing engineer is exactly the same. From this point of view, the computing engineer should stop asking "How can I make an intelligent machine?" because he is, in fact, doing it at this very moment, and has been doing it for the last twenty years. He should stop being overwhelmed by the so-called geniuses, and he should realize that the so-called genius is simply a rather extreme example of the system towards which he is working steadily. He will doubtless soon develop machines other than the large digital, but these will simply be intelligent in other ways. The contrast here is not between digital and analogue, or germanium vs protein, but between the true intelligence that processes information in due quantities, and the merely mythical intelligence that human beings have sometimes supposed themselves to possess.

A second application of the basic postulate is that it will provide guidance in a host of different processes. For one must realize that the rule about appropriate selection applies not merely to the final goal, but to all the sub­goals that have to be found on the way to it, and to all the qualifying goals that may be set up. Thus, if the goal is a program to play good chess, the programmer may soon add a subsidiary goal:—the program is to be achieved in the
shortest time. Now this "shortest time" is itself a goal, and its achievement demands appropriate selection (among the various ways that consume various times). Thus this demand itself can be met only by processing of the relevant information in sufficient quantity. If the information (about the relative quicknesses) does not exist in 1960, then the appropriate selection cannot be made. If the goal (of the quickest way) is still desirable, there is no way but that information must be collected. This means that there is no other way than that the program writer should try a tape, see how long it takes, try another tape, see how long it takes, and either by trial and error (another name for "experiment") or in any other way available to him, get the information about which way is the quickest.

There are a host of these subsidiary questions usually coming up during any real appropriate selection, and they can be extremely troublesome. It is a part of what I am saying that the basic postulate will apply to all of these subsidiary questions.

Any attempt to achieve a major goal usually implies the achieving of many minor or qualifying goals. The basic postulate, and the law of requisite variety cover them all. For example, to conduct a search quickly (with speed as the qualifying goal) may require repeated dichotomization. Then "how to dichotomize" becomes the object of a search. Finding how is an act of appropriate selection; it is again subject to the postulate.

There is again the problem of where to bring back corrective feedbacks: Should the correction be fed back to this point or to that? To know which is to make an act of appropriate selection, and this again can be done only insofar as information exists. If it does not exist either a simple random decision must be made or further information must be obtained, either systematically or unsystematically by trial and error; and so on, again and again.

To sum up. What is often referred to with bated breath as "real" intelligence, is a myth. The human being saves himself from being wholly foolish by having a great deal of information, as preprogramming, derived from millions of years of evolution on this earth, and by his personal experience over decades. Give him a problem in this range and he is really slick. This is his real intelligence. And any machine equally preprogrammed has an equal amount of real intelligence.

But this intelligence, whether of man or machine, is absolutely bounded. And what we can build into our machines is similarly bounded. The amount of intelligence we can get into a machine is absolutely bounded by the quantity of information that is put into it. We can get out of a machine as much intelligence as we like, if and only if we insure that at least the corresponding quantity of information gets into it.

The thought of this ultimate limitation is sobering, but the situation here today is not unlike that of power engineering a century ago.

At that time, so many powerful machines were being developed that many engineers took it for granted that the perpetual motion machine would soon be discovered. Then gradually emerged the idea that energy could not be created; and I have little doubt that this idea was seriously disappointing to many of the engineers of the time. They regarded it simply as a limitation.

Nevertheless, we now know that those engineers who accepted the limitation were in fact more realistic than those who went on hoping that perpetual motion would be possible. In the long run, the engineers who accepted it built better engines than those who went on struggling after perpetual motion. I suggest that today the position in computing is similar. If we accept the limitation—that appropriate selection can be achieved only to the degree that information is received and processed—and if we accept that this limitation holds absolutely over all brains, human and mechanical, our work, though less intoxicating, will in fact be more realistic. Those who build intelligent machines on this basis will outdistance those who want to build them on the old and superstitious basis that the human brain can do anything.

References