The discussion up to this point has provided the basis for the comparison that is the objective of this work. I have described, in some detail, the nature of modern computing machines and the broad alternative principles around which they can be organized. It is now possible to pass on to the other term of the comparison, the human nervous system. I will discuss the points of similarity and dissimilarity between these two kinds of “automata.” Bringing out the elements of similarity leads over well-known territory. There are elements of dissimilarity, too, not only in rather obvious respects of size and speed but also in certain much deeper-lying areas: These involve the principles of functioning and control, of over-all organization, etc. My primary aim is to develop some of these. However, in order to appreciate them properly, a juxtaposition and combination with the points of similarity, as well as with those of more superficial dissimilarity (size, speed; cf. above) are also required. Hence the discussion must place considerable emphasis on these, too.

Simplified Description of the Function of the Neuron

The most immediate observation regarding the nervous system is that its functioning is prima
facie digital. It is necessary to discuss this fact, and the structures and functions on which its assertion is based, somewhat more fully.

The basic component of this system is the nerve cell, the neuron, and the normal function of a neuron is to generate and to propagate a nerve impulse. This impulse is a rather complex process, which has a variety of aspects—electrical, chemical, and mechanical. It seems, nevertheless, to be a reasonably uniquely defined process, i.e. nearly the same under all conditions; it represents an essentially reproducible, unitary response to a rather wide variety of stimuli.

Let me discuss this—i.e. those aspects of the nerve impulse that seem to be the relevant ones in the present context—in somewhat more detail.


the Nature of the Nerve Impulse

The nerve cell consists of a body from which originate, directly or indirectly, one or more branches. Such a branch is called an axon of the cell. The nerve impulse is a continuous change, propagated—usually at a fixed speed, which may, however, be a function of the nerve cell involved—along the (or rather, along each) axon. As mentioned above, this condition can be viewed under multiple aspects. One of its characteristics is certainly that it is an electrical disturbance; in fact, it is most frequently described as being just that. This disturbance is usually an electrical potential of something like 50 millivolts and of about a millisecond's
duration. Concurrently with this electrical disturbance there also occur chemical changes along the axon. Thus, in the area of the axon over which the pulse-potential is passing, the ionic constitution of the intracellular fluid changes, and so do the electrical-chemical properties (conductivity, permeability) of the wall of the axon, the membrane. At the endings of the axon the chemical character of the change is even more obvious; there, specific and characteristic substances make their appearance when the pulse arrives. Finally, there are probably mechanical changes as well. Indeed, it is very likely that the changes of the various ionic permeabilities of the cell membrane (cf. above) can come about only by reorientation of its molecules, i.e. by mechanical changes involving the relative positions of these constituents.

It should be added that all these changes are reversible. In other words, when the impulse has passed, all conditions along the axon, and all its constituent parts, resume their original states.

Since all these effects occur on a molecular scale—the thickness of the cell membrane is of the order of a few tenth-microns (i.e. $10^{-8}$ cm.), which is a molecular dimension for the large organic molecules that are involved here—the above distinctions between electrical, chemical, and mechanical effects are not so definite as it might first appear. Indeed, on the molecular scale there are no sharp distinctions between all these kinds of changes; every chemical change is induced by a change in intramolecular forces which determine changed relative positions of the molecules, i.e. it is
mechanically induced. Furthermore, every such intramolecular mechanical change alters the electrical properties of the molecule involved, and therefore induces changed electrical properties and changed relative electrical potential levels. To sum up: on the usual (macroscopic) scale, electrical, chemical, and mechanical processes represent alternatives between which sharp distinctions can be maintained. However, on the near-molecule level of the nerve membrane, all these aspects tend to merge. It is, therefore, not surprising that the nerve impulse turns out to be a phenomenon which can be viewed under any one of them.

THE PROCESS OF STIMULATION

As I mentioned before, the fully developed nerve impulses are comparable, no matter how induced. Because their character is not an unambiguously defined one (it may be viewed electrically as well as chemically, cf. above), its induction, too, can be alternatively attributed to electrical or to chemical causes. Within the nervous system, however, it is mostly due to one or more other nerve impulses. Under such conditions, the process of its induction—the stimulation of a nerve impulse—may or may not succeed. If it fails, a passing disturbance arises at first, but after a few milliseconds, this dies out. Then no disturbances propagate along the axon. If it succeeds, the disturbance very soon assumes a (nearly) standard form, and in this form it spreads along the axon. That is to say, as mentioned above,
a standard nerve impulse will then move along the
axon, and its appearance will be reasonably inde-
pendent of the details of the process that induced it.
The stimulation of the nerve impulse occurs
normally in or near the body of the nerve cell. Its
propagation, as discussed above, occurs along the
axon.

THE MECHANISM OF STIMULATING PULSES BY
PULSES; ITS DIGITAL CHARACTER

I can now return to the digital character of this
mechanism. The nervous pulses can clearly be
viewed as (two-valued) markers, in the sense dis-
cussed previously: the absence of a pulse then
represents one value (say, the binary digit 0), and
the presence of one represents the other (say, the
binary digit 1). This must, of course, be interpreted
as an occurrence on a specific axon (or, rather, on
all the axons of a specific neuron), and possibly in
a specific time relation to other events. It is, then,
to be interpreted as a marker (a binary digit 0 or
1) in a specific, logical role.

As mentioned above, pulses (which appear on
the axons of a given neuron) are usually stimu-
lated by other pulses that are impinging on the
body of the neuron. This stimulation is, as a rule,
conditional, i.e. only certain combinations and
synchronisms of such primary pulses stimulate
the secondary pulse in question—all others will
fail to so stimulate. That is, the neuron is an organ
which accepts and emits definite physical entities,
the pulses. Upon receipt of pulses in certain combinations and synchronisms it will be stimulated to emit a pulse of its own, otherwise it will not emit. The rules which describe to which groups of pulses it will so respond are the rules that govern it as an active organ.

This is clearly the description of the functioning of an organ in a digital machine, and of the way in which the role and function of a digital organ has to be characterized. It therefore justifies the original assertion, that the nervous system has a *prima facie* digital character.

Let me add a few words regarding the qualifying "prima facie." The above description contains some idealizations and simplifications, which will be discussed subsequently. Once these are taken into account, the digital character no longer stands out quite so clearly and unequivocally. Nevertheless, the traits emphasized in the above are the primarily conspicuous ones. It seems proper, therefore, to begin the discussion as I did here, by stressing the digital character of the nervous system.

**TIME CHARACTERISTICS OF NERVE RESPONSE, FATIGUE, AND RECOVERY**

Before going into this, however, some orienting remarks on the size, energy requirements, and speed of the nerve cell are in order. These will be particularly illuminating when stated in terms of comparisons with the main "artificial" competitors: The typical active organs of modern logical and
computing machines. These are, of course, the vacuum tube and (more recently) the transistor.

I stated above that the stimulation of the nerve cell occurs normally on or near its body. Actually, a perfectly normal stimulation is possible along an axon, too. That is, an adequate electrical potential or a suitable chemical stimulant in adequate concentration, when applied at a point of the axon, will start there a disturbance which soon develops into a standard pulse, traveling both up and down the axon, from the point stimulated. Indeed, the "usual" stimulation described above mostly takes place on a set of branches extending from the body of the cell for a short distance, which, apart from their smaller dimensions, are essentially axons themselves, and it propagates from these to the body of the nerve cell (and then to the regular axons). By the way, these stimulation-receptors are called dendrites. The normal stimulation, when it comes from another pulse (or pulses) emanates from a special ending of the axon (or axons) that propagated the pulse in question. This ending is called a synapse. (Whether a pulse can stimulate only through a synapse, or whether, in traveling along an axon, it can stimulate directly another, exceptionally close-lying axon, is a question that need not be discussed here. The appearances are in favor of assuming that such a short-circuited process is possible.) The time of trans-synaptic stimulation amounts to a few times $10^{-4}$ seconds, this time being defined as the duration between the arrival of a pulse at a synapse and the appearance of the stimulated pulse on the nearest point of an
axon of the stimulated neuron. However, this is not the most significant way to define the reaction time of a neuron, when viewed as an active organ in a logical machine. The reason for this is that immediately after the stimulated pulse has become evident, the stimulated neuron has not yet reverted to its original, prestimulation condition. It is fatigued, i.e. it could not immediately accept stimulation by another pulse and respond in the standard way. From the point of view of machine economy, it is a more important measure of speed to state after how much time a stimulation that induced a standard response can be followed by another stimulation that will also induce a standard response. This duration is about \(1.5 \times 10^{-4}\) seconds. It is clear from these figures that only one or two per cent of this time is needed for the actual trans-synaptic stimulation, the remainder representing recovery time, during which the neuron returns from its fatigued, immediate post-stimulation condition to its normal, prestimulation one. It should be noted that this recovery from fatigue is a gradual one—already at a certain earlier time (after about .5 times \(10^{-5}\) seconds) the neuron can respond in a nonstandard way, namely it will produce a standard pulse, but only in response to a stimulus which is significantly stronger than the one needed under standard conditions. This circumstance has somewhat broad significance, and I will come back to it later on.

Thus the reaction time of a neuron is, depending on how one defines it, somewhere between \(10^{-4}\) and
10⁻⁴ seconds, but the more significant definition is the latter one. Compared to this, modern vacuum tubes and transistors can be used in large logical machines at reaction times between 10⁻⁴ and 10⁻⁵ seconds. (Of course, I am allowing here, too, for the complete recovery time; the organ in question is, after this duration, back to its prestimulation condition.) That is, our artifices are, in this regard, well ahead of the corresponding natural components, by factors like 10⁴ to 10⁶.

With respect to size, matters have a rather different aspect. There are various ways to evaluate size, and it is best to take these up one by one.

SIZE OF A NEURON. COMPARISONS WITH ARTIFICIAL COMPONENTS

The linear size of a neuron varies widely from one nerve cell to the other, since some of these cells are contained in closely integrated large aggregates and have, therefore, very short axons, while others conduct pulses between rather remote parts of the body and may, therefore, have linear extensions comparable to those of the entire human body. One way to obtain an unambiguous and significant comparison is to compare the logically active part of the nerve cell with that of a vacuum tube, or transistor. For the former this is the cell membrane, whose thickness as mentioned before is of the order of a few times 10⁻⁸ cm. For the latter it is as follows: in the case of the vacuum tube, it is the grid-
to-cathode distance, which varies from $10^{-3}$ to a few times $10^{-2}$ cm.; in the case of the transistor, it is the distance between the so-called “whisker electrodes” (the non-ohmic electrodes—the “emitter” and the “control-electrode”), about 3 folded in order to account for the immediate, active environment of these subcomponents, and this amounts to somewhat less than $10^{-3}$ cm. Thus, with regard to linear size, the natural components seem to lead our artifacts by a factor like $10^4$.

Next, a comparison with respect to volume is possible. The central nervous system occupies a space of the order magnitude of a liter (in the brain), i.e. of $10^7$ cm.$^3$. The number of neurons contained in this system is usually estimated to be of the order of $10^{10}$, or somewhat higher. This would allow about $10^{-7}$ cm.$^3$ per neuron.

The density with which vacuum tubes or transistors can be packed can also be estimated—although not with absolute unambiguity. It seems clear that this packing density is (on either side of the comparison) a better measure of size efficiency than the actual volume of a single component. With present-day techniques, aggregates of a few thousand vacuum tubes will certainly occupy several times 10 ft.$^3$; for transistors the same may be achieved, in something like one, or a few, ft.$^3$. Using the figure of the latter order as a measure of the best that can be done today, one obtains something like $10^4$ cm.$^3$ for a few times $10^4$ active organs, i.e. about 10 to $10^6$ cm.$^3$ per active organ. Thus the natural components lead the artificial ones with respect to volume requirements by factors like $10^8$ to $10^9$. In comparing this with the estimates for the
linear size, it is probably best to consider the linear size-factor as being on one footing with the cube root of the volume-factor. The cube root of the above $10^8$ to $10^9$ is .5 to 1 times $10^8$. This is in good accord with the $10^8$ arrived at above by a direct method.

**ENERGY DISSIPATION. COMPARISONS WITH ARTIFICIAL COMPONENTS**

Finally, a comparison can be made with respect to energy consumption. An active logical organ does not, by its nature, do any work: the stimulated pulse that it produces need not have more energy than the prorated fraction of the pulses which stimulate it—and in any case there is no intrinsic and necessary relationship between these energies. Consequently, the energy involved is almost entirely dissipated, i.e. converted into heat without doing relevant mechanical work. Thus the energy consumed is actually energy dissipated, and one might as well talk about the energy dissipation of such organs.

The energy dissipation in the human central nervous system (in the brain) is of the order of 10 watts. Since, as pointed out above, the order of $10^8$ neurons are involved here, this means a dissipation of $10^{-8}$ watts per neuron. The typical dissipation of a vacuum tube is of the order of 5 to 10 watts. The typical dissipation of a transistor may be as little as $10^{-3}$ watts. Thus the natural components lead the artificial ones with respect to dissipation by factors like $10^3$ to $10^8$—the same factors that appeared above with respect to volume requirements.
SUMMARY OF COMPARISONS

Summing up all of this, it appears that the relevant comparison-factor with regard to size is about $10^9$ to $10^6$ in favor of the natural componentry versus the artificial one. This factor is obtained from the cube of a linear comparison, as well as by a volume-comparison and an energy-dissipation comparison. Against this there is a factor of about $10^4$ to $10^6$ on speed in favor of the artificial componentry versus the natural one.

On these quantitative evaluations certain conclusions can be based. It must be remembered, of course, that the discussion is still moving very near to the surface, so that conclusions arrived at at this stage are very much subject to revision in the light of the further progress of the discussion. It seems nevertheless worth while to formulate certain conclusions at this point. They are the following ones.

First: in terms of the number of actions that can be performed by active organs of the same total size (defined by volume or by energy dissipation) in the same interval, the natural componentry is a factor $10^6$ ahead of the artificial one. This is the quotient of the two factors obtained above, i.e. of $10^8$ to $10^6$ by $10^4$ to $10^6$.

Second: the same factors show that the natural componentry favors automata with more, but slower, organs, while the artificial one favors the reverse arrangement of fewer, but faster, organs. Hence it is to be expected that an efficiently organ-
ized large natural automation (like the human nervous system) will tend to pick up as many logical (or informational) items as possible simultaneously, and process them simultaneously, while an efficiently organized large artificial automaton (like a large modern computing machine) will be more likely to do things successively—one thing at a time, or at any rate not so many things at a time. That is, large and efficient natural automata are likely to be highly parallel, while large and efficient artificial automata will tend to be less so, and rather to be serial. (Cf. some earlier remarks on parallel versus serial arrangements.)

Third: it should be noted, however, that parallel and serial operation are not unrestrictedly substitutable for each other—as would be required to make the first remark above completely valid, with its simple scheme of dividing the size-advantage factor by the speed-disadvantage factor in order to get a single (efficiency) "figure of merit." More specifically, not everything serial can be immediately paralleled—certain operations can only be performed after certain others, and not simultaneously with them (i.e. they must use the results of the latter). In such a case, the transition from a serial scheme to a parallel one may be impossible, or it may be possible but only concurrently with a change in the logical approach and organization of the procedure. Conversely, the desire to serialize a parallel procedure may impose new requirements on the automaton. Specifically, it will almost always create new memory requirements, since the results of the operations that are performed first
must be stored while the operations that come after these are performed. Hence the logical approach and structure in natural automata may be expected to differ widely from those in artificial automata. Also, it is likely that the memory requirements of the latter will turn out to be systematically more severe than those of the former.

All these viewpoints will reappear in the discussions that are to follow.

Stimulation Criteria

The Simplest—Elementary Logical

I can now turn to the discussion of the idealizations and simplifications contained in the description of nerve-action as it was given further above. I pointed out there that these existed and that their implications are not at all trivial to evaluate.

As pointed out before, the normal output of a neuron is the standard nerve pulse. This can be induced by various forms of stimulation, including the arrival of one or more pulses from other neurons. Other possible stimulators are phenomena in the outside world to which a particular neuron is specifically sensitive (light, sound, pressure, temperature), and physical and chemical changes within the organism at the point where the neuron is situated. I will begin by considering the first-mentioned form of stimulation—that by other nerve pulses.

I observed before that this particular mechanism—the stimulation of nerve pulses by suitable com-