Information Processing in the Nervous System

The nervous system, limited in its ability to process sensory data, must operate selectively and economically.

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The study of the nervous system can be carried out in at least three major ways. First, one may examine the *physiological* mechanisms by detecting the electrical and chemical events that go on in the system while it is operating. Second, one may examine the *behavior* of a man or animal from outside, either by observing what occurs spontaneously or by devising experimental situations which will throw certain functions into relief. Third, one can devise mechanical or mathematical analogies and *models* for processes similar to those performed by nervous systems; this type of study can be carried out as an end in itself, in order to produce effective machines, or it may be deliberately pursued as shedding light on the processes in nervous systems which are found in nature. All these three approaches are of value, and no one of them should be neglected.

Although such statements may seem trite, there is undoubtedly a tendency for specialists in any one field to undervalue the other two. This tendency should always be resisted: it is idle to devise theoretical mechanisms to explain the brain without considering the actual functions which real nervous systems perform and the mechanisms that they have available to do so. It is equally useless to consider behavior alone without reference to mechanisms which are known to exist from physiology, or to those which can be logically devised to perform a certain function. Finally, it is unprofitable simply to consider the physiology of the nervous system and the various things which such components might conceivably do without examining the behavior of animals or men to see what they really can do. It should therefore be borne in mind that the following remarks are written from the point of view of a student of behavior and that the physiologist or automaton theorist could add a great deal to each of the topics mentioned.

It now goes almost without saying that these three approaches find a common language for discussing the nervous system by using the language of information processing. If we discuss only the electrical and chemical changes in nerves produced by certain disturbances at the sense organs, there may seem little in common with any statement in the language of traditional psychology. There may seem no point of contact between, on the one hand, the occurrence of light of a certain wavelength followed by a particular distribution of nervous impulses and, on the other hand, the experience of seeing red. In informational language, however, we can take a unified view of the nervous system.

We think, then, of a set of different possible environments, one of which is actually confronting a particular nervous system at a particular time; and there is a set of possible outputs which the system might make, one of which it actually does make on a particular occasion. If there is a perfect correspondence between the set of outputs and the set of possible input situations, so that the animal or man always produces a response which is unique to the situation in which he finds himself, then a similar correspondence must equally apply at every stage within the nervous system. It will of course be more usual for events within the nervous system to correspond to the particular input only up to a certain point, and for rather complex changes and transformations to take place before the output occurs, just as the output of a computer will be the result of a series of complicated operations performed upon the input that is delivered to it. However, by considering sets of alternatives at each point of the system and the way in which one element out of the set is selected when a particular element occurs at a previous stage, we can pass easily from physiological to psychological problems, and to mechanical analogies.

Limits of Capacity

Such a description of the functioning of nervous systems immediately raises the point that there is a very large variety of different possible situations in which an animal or man may be placed. Since most nervous systems are reasonably small, there is almost bound to be a problem of providing a set of different possible states of the brain which will correspond to a sufficiently large number of different possible states of the environment. It is not sufficient, say, simply to take each sensory cell in the retina of the eye and to make some further cell in the brain active or inactive depending upon the state of the retinal cell. As has been a problem for many previous approaches, patterns of stimulation can be consistently recognized, so that an environment containing a triangle can consistently produce a different reaction from an environment containing a square, even though the shape falls on a quite different part of the eye on each occasion it is seen. It is possible to devise mechanical systems which would perform such a discrimination, and even to produce hypothetical systems which might in principle learn to make the discrimination from an original randomly connected state. Such, for example, is the perceptron, in which each of a set of sensory elements is connected randomly with several association elements later in the system (*1*). Some of these association elements will receive information from combinations of sensory elements, so that there might well be some association element which would become active whenever a triangle was presented in one location, another when a rather different location was used, and so on. With some suitable modification of

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the interconnections, following "right" and "wrong" outputs, such a system might well discriminate triangles and squares anywhere on the sensory surface; but it would need a very large number of association elements to do so.

The problem of *capacity*, the size of the set of available states within the nervous system, thus becomes very serious, and this is true of most systems of pattern recognition that have been suggested. Indeed, I have minimized the problem by supposing simply that the retina receives a square or triangular set of stimuli; whereas in fact the sides of a square or triangular pattern will probably be distorted more or less severely before they reach the sense organs on the retina. This will happen because the eye will probably not view the pattern directly at right angles, and even in the exceptional cases when it is seen straight on, the optical characteristics of the eye will introduce some distortion of their own. A complete set of mechanisms for calculating back from the pattern of stimulation on the retina, to the original pattern of events in the outside world which must have produced this distorted pattern on the retina, must therefore be supposed.

Although visual examples have been taken because of their familiarity, similar difficulties arise in other senses as well. Thus in the perception of speech, the identification of different vowel sounds depends upon the detection of the relative position of resonant frequencies in different parts of the spectrum, so that the problem is very similar to that of discriminating squares from triangles; and, furthermore, there are compensatory mechanisms which take account of the fact that one may be listening to a person with a large or small head, so that the sounds which one speaker produces may be shifted up or down the range of audible frequencies, as compared with those which another speaker produces. The machinery necessary to recognize patterns must therefore be multiplied even further so as to cope with all the senses; and indeed some experiments have shown that the understanding of speech is less efficient if the listener cannot see the lips of the talker, even for ordinary listeners who do not realize that they are lip reading. Thus the mechanisms of analysis must be capable of dealing with combinations of stimulation by different senses, in addition to patterns of stimulation within a sense. On general principles, therefore, it seems that a major feature of information processing in the nervous system should be procedures for economizing in mechanism.

Input Selection and Interference

Purely a priori arguments such as those I have been advancing are by themselves rather unconvincing. Fortunately, however, there are certain areas of behavior in which one can show experimentally phenomena which seem reasonable if limits of capacity are a problem for the nervous system. One device which might be expected, for example, is the use of the same components to serve different functions at different times. This would mean that the system would be capable of carrying a variety of tasks, but not of doing them simultaneously. Although there are indeed some cases in which information is processed in parallel and simultaneously, there are a number of experiments in which one can show that two tasks performed at the same time create difficulty for one another. To take an initial example from outside the laboratory, it has been shown that the ability of a pilot to fly a prescribed maneuver on instruments is better when the radio communication system to which he also has to listen is arranged so as to be more easily intelligible (*2*). Listening to speech sounds interferes in some way with viewing instruments and making control movements. This kind of effect is sufficiently widespread for applied psychologists to have made considerable use of it in recent years as a method of measuring the difficulty of tasks (*3*). While the man is doing some job, such as driving an automobile in particular traffic conditions, he is also asked to carry out some other task which does not use the same senses or limbs, and the efficiency with which he does the second task is taken as a measure of the difficulty of the first one.

An overall score of the efficiency of instrument flying, or of the number of questions answered while simultaneously driving a car, does not give us a really detailed picture of what is going on in the nervous system. Laboratory tasks can be made more analytic: as a step in the direction of abstraction, consider somebody who is asked to call out letters of the alphabet in random order while simultaneously sorting a deck of playing cards into separate red and black piles (*4*). He will not, of course, be successful in calling out the letters quite randomly, but rather will show a disproportionate tendency to produce such habitual responses as following one letter by the letter immediately preceding it in the alphabet. We can measure the percentage of such stereotyped responses, or indeed calculate the information transmitted overall by his calling of letters, and if we do so we find that the departure from randomness depends upon the nature of the other simultaneous task. If the deck of cards has to be sorted into the four suits rather than into two colors, then the man is less able to call out letters at random: while if the deck had to be sorted into eight categories, the calling of letters would be still more stereotyped. Thus the extent to which task A interferes with task B depends upon the number of different alternative states of the environment that may be involved in task A, the number of such states in turn presumably affecting the number of different possible states of the nervous system that have to be reserved for that task in order to allow efficient performance.

Therefore when some task involving a good deal of information has to be performed, such as listening to a rather unpredictable speech, or indeed reading a paper such as the present one, successful performance requires the elimination of other activities. One technique to achieve this end is of course adjustment of the sense organs, such as wearing ear plugs when one is reading or closing the eyes when listening. It is not therefore too surprising to find experimentally that performance of a complex task is easier when all the relevant information arrives by some particular channel, while other irrelevant information does not arrive by the same channel. For example, if one has to answer a series of questions which are accompanied by other quite irrelevant speech, it is easier to do so when the questions are delivered to one ear and the irrelevant speech to the other ear than when both are mixed into the same ear (*2*, pp. 11–35).

There has been much interest on the part of physiologists in the past decade in the possibility that the sensitivity of sense organs may be controlled directly by outgoing messages proceeding from the brain to the sense organ, in the opposite direction to the more familiar messages traveling from the sense organs into the brain. It is somewhat difficult to distinguish direct effects on the senses produced in this way from indirect effects such as change in the size of the pupil of the eye and in the tension of the muscles which adjust the eardrum. However, in the case of the ear there does seem satisfactory evidence that the sensitivity of the sense organ itself can be changed (*5*). Thus it is conceivable that the nervous system actually switches off one ear in order to listen to the other and thus preserves the central mechanisms of limited capacity from the interference which would otherwise arise. Such change in sensitivity of the sense organs themselves is undoubtedly not the whole story, since, for example, a man will find it easier to listen to one message and ignore another if the two messages are made to appear to come from different directions by altering the time relations between stimulation of the two ears (*6*). In this case, each ear is in fact receiving both messages, and turning off one ear would not help. The signals reaching the two ears must be admitted to the nervous system, combined in such a way as to detect the two apparently separated sources of sound, and only then is the information from one voice passed on for further processing while that from the other voice is not. As yet the physiological basis of this more central filtering process is not understood.

There seems evidence in behavior, therefore, that indeed the nervous system admits only part of the information reaching the sensory organs, and much of the remainder is lost. A most important part of the learning which goes on during life is the selection of the particular information which is going to be of the greatest use at any particular time, and it is at least logically possible that the principles governing such learning will be rather different from those which govern the learning of one action rather than another. Sutherland and Mackintosh have recently conducted a major series of experiments on animal learning, which do indeed suggest that this is so (*7*). One kind of experiment which has long aroused interest, for example, is to train an animal until it is performing perfectly to go through a black rather than a white door when given a choice, and then to teach it the exactly opposite action, to go to white and avoid black. Additional training on the original discrimination, after performance is perfect, may increase the speed with which the opposite learning takes place. This only happens, however, if the two doors differ in a large number of other ways, such as being of different shapes, although these other qualities tell the animal nothing about whether the particular door is the correct one or not. Thus the extra training seems to be affecting the ability to select the right information, to notice the color of the door rather than its shape, and it seems to be having a much larger effect upon the selection than it is upon the actual response of approach or avoidance which is made to a particular color.

I have somewhat oversimplified the situation by talking as if the nervous system shut off information coming from certain sources and let through only that from other sources: because there is a rather different selective process, which also has the effect of economizing in the capacity necessary, and this reveals itself in the fact that a listener will hear his own name even when the name occurs in speech which he is ignoring in order to concentrate on some other message (*8*). Thus a nervous system which is admitting information from one source is not completely indifferent to what is going on elsewhere in its surroundings, but seems able to make some responses even to information from other sources. These responses can be regarded as those towards which the system is for one reason or another biased, and this can perhaps be best understood in the light of certain other features of information processing which should now be considered.

Combating Random Disturbance

An actual nervous system differs from many machines in the degree of reliability of its components. The parts of which it is made are not turned out to a standardized pattern, like pieces of an automobile, but rather may show a range of variability like the range of different bodily sizes which we are accustomed to encountering in our everyday dealings with people. Biological components may also change in state from time to time, depending upon the general chemical condition of the body, and also on momentary factors. Thus for example a nerve fiber has to recover after the passage of each impulse, and on a larger time scale a number of cells in our brain die each day as we get older. One cannot therefore rely on any particular component's performing as it should on any particular occasion, and processing must take a form which is resistant to this kind of random interference. A technique which machines may use for this purpose is to send any message through a system several times by different routes, so that there are several different components involved and the failure of any one of them will not ruin the whole operation. This principle is of course employed in important man-made devices, such as automatic blind-landing systems for aircraft, but it does involve a large increase in the number of components necessary to carry out any particular operation. Theoretical analysis of the most economical way of combating unreliability of components has shown that it can be done most efficiently by making the activity of any component at one stage in the process depend upon the activity of several different components at an earlier stage, rather than by making each component at one stage depend upon one component at an earlier stage (*9*). This means that, if we have an array of sensory cells as in the retina of the eye, we ought to expect that stimulation of any one point would not merely produce activity in a single fiber leading into the brain from that point, but also should produce modifications in other adjacent fibers, which are also affected by other points on the retina. Such lateral interconnection has of course long been evident both anatomically and from physiological observation, and it represents an economical method of combating random disturbances in transmission.

Even with such devices in play, however, the message reaching some point deep in the nervous system may not be a completely reliable indicator of the presence or absence of some particular event at the senses. This has long been recognized, since a man will not always hear a sound that is presented in the region of the faintest sounds he can hear, although he will sometimes do so. Until recently it has usually been supposed in such cases that the event inside the nervous system corresponding to "hearing the sound" only occurred when the sound was really there, although sometimes it might not occur even then. Admittedly, people who are asked to listen for faint sounds do sometimes report hearing something even when nothing is presented, but this has usually been regarded as a reprehensible tendency to guess and has been discouraged in careful experiments on the limits of the senses. This interpretation might be regarded as supported by the fact that such "false positives" become more frequent if the man has reason to believe that a sound is probable, or if he is given a financial reward for hearing sounds and only fined some smaller amount for reporting something which is not there. However, if this interpretation were correct, then if we change the amount of reward and so change the number of false positives, the corresponding change in the number of correct reports of a sound should be proportional to the change in false positives. It should also be rather less than that change. In a large number of cases, neither of these expectations is fulfilled; the change in the number of correct detections is at first much larger than in that of false positives, and then becomes less when the false-positive rate is high (*10*).

There are various possible interpretations of this experimental result, but it is clear that the traditional view is completely out of court. The possible explanations which have been put forward usually involve the idea that the report of hearing a sound is based on events inside the nervous system which are inherently rather unreliable indications of what is going on at the senses. This evidence then produces the response "I hear a sound" on principles which minimize the ill effects of the randomness. One particularly widely held view, for example, is that the output occurs whenever the evidence within the nervous system exceeds a critical value C such that the ratio of the probability of C given a signal to the probability of C given no signal is sufficiently high. This critical value is supposed to decrease when signals are more likely and when detecting them secures a larger reward. It would be rational for it to do so, according to statistical decision theory. A critical level moving in this way would secure the greatest possible advantage given the degree of unreliability in the system that is present.

On this view, there are two quite independent ways in which the frequency of detection of signals may be changed. One of them is by changes in the critical value already mentioned, and the other is by changes in the reliability of the evidence delivered by the senses to the central mechanisms. If the changes are due to the first of these causes, an increase in detections will usually be accompanied by an increase in false positives, while if they are due to the second, it may not, and may even be accompanied by a decrease. Experiment shows, as already mentioned, that changes in the probability of a signal or in the payoffs for being right and wrong will produce the first kind of change; while it is also found that changes in the physical strength of a stimulus will produce the second kind of change (*11*). Even if the mechanism which produces these changes is not analogous to a statistical decision process, it certainly has these two modes of operation.

At this stage, we can return to the selective processes which allow only certain information entering the nervous system to be analyzed. By presenting a rather inconspicuous signal to one ear of the listener, and asking him to report when he hears it, we can measure the correct detections and false positives and so obtain a measure of his performance when he is concentrating upon the signal. We can also deliver speech to his other ear and compare his performance on the one hand when he is told to ignore this speech, and on the other hand when he is told to reproduce the speech as well as to report the presence or absence of tone. In looking at the results, we can then ask whether division of attention has changed the critical level, or the reliability of the evidence, in terms of the statistical theory of perception mentioned a little earlier. In other words, does division of attention produce a change like that produced by a change in the probability of a signal, or like that produced by a change in the strength of the signal? In fact, experiment shows that the latter is the case, and therefore that the paying of attention to one ear apparently has an effect comparable to increasing or decreasing the sensitivity of the sense organ (*12*).

On the other hand, it has already been pointed out that a man does hear his own name even in a conversation to which he is not listening, or more generally, will hear words which are at that moment very probable, even if his attention is not directed towards the sense organ to which they are delivered (*8, 13*). It is tempting to suppose that this is because there has been a change in the critical level for some words as opposed to others, which means that they will be perceived even when the evidence in their favor is relatively slight. Indeed, some direct experimental evidence has been produced to support such a view, by an analysis of the proportions of correct perceptions and of different kinds of error when words of different probability are presented through a noise which makes them difficult to hear (*14*).

In general, therefore, it can be accepted that the unreliability of the nervous system causes a certain number of false perceptions, but that the ill effects of this are minimized by the nature of the mechanism which translates the evidence provided by the senses into a percept.

Choice of Appropriate Actions

If we ask a man not simply to perceive what happens in some situation, but to take an action about it, we can measure how long his decision takes. In simple cases, we may tell him that we are going to light one of a number of lamps and that he is to press one of a number of corresponding buttons. Such a process might seem too simple to deserve the name of decision, since the correct action appears almost unconsciously, and one might almost suppose that the time taken between stimulation and response is taken up in neural transmission processes of no great psychological interest. However, there are some features of choice-reaction time which are related to the problem of limited capacity of the nervous system and to the means of economy which one must therefore expect the system to employ. In a variety of situations, reaction time increases as the number of alternative possible actions increases, but does so as a logarithmic function of the number of alternatives. If we want to send one of a fixed set of messages along a telegraph wire, using a small or fixed vocabulary of symbols, the length of the coded message proceeding along the telegraph wire will increase logarithmically with the number of different possible messages from which we chose the one we actually sent. Thus the similar relationship found in choice-reaction time has caused many investigators to regard it as evidence that the nervous system is limited in capacity, just as the fixed set of symbols limits the capacity of the telegraph channel, and that the code is adjusted efficiently to fit the particular situation in which the man is reacting at any given time. There are, however, certain detailed features of the experimental results which are not covered by such a view.

For example, if the man is pressed to react to a series of signals delivered to him at a fixed speed regardless of his own response, he seems to reach maximum efficiency at a response rate of two or three actions per second, even when the number of alternative actions among which he is choosing is varied (*15*). Perhaps most important, however, are the results of a number of recent experiments which have shown that a highly practiced task gives less increase in reaction time as the number of alternative possible actions is doubled than does an unpracticed task. This applies even if the particular job has never been performed by the man before, but nevertheless seems natural to him because the reaction required bears a relationship to the stimulus that he has often met previously. For example, if we flash a series of numbers on a screen, and the man has a row of keys in front of him, it will be easy and natural for him if the correct response to the number 4 is the fourth key from the left, and so on, rather than having keys numbered randomly. Such "compatible" relationships between stimulus and response show much less effect on reaction time when the number of possible responses is increased (*16*).

This kind of result has caused some investigators to put forward theories of the choice between different actions which are closely similar mathematically to the theories of detection of signals mentioned in the last section. It is a familiar general principle that, when one is collecting rather unreliable evidence, one can increase its reliability by taking the average of a number of observations over a longer period of time. If we look at two highways in order to see which is carrying the more traffic, one day's observation may conceivably give us the wrong answer; at the opposite extreme, a full year's observation is very likely indeed to give us the correct answer. In such a situation there are in fact statistical techniques which will allow us to go on watching for a number of days until the difference in the average traffic we have observed becomes sufficiently great to exceed a critical level of confidence, so that we may safely conclude that any further observations would not change the conclusion we have reached.

If we now think of a nervous system faced with two possible stimuli and two reaction keys, we may suppose that the application of a stimulus does not produce a completely determinate and reliable chain of events leading automatically to the correct reaction, but rather that there is a certain amount of uncertainty and unreliability about the messages traveling from the senses to the centers controlling action. The less practiced or compatible the situation, the greater this uncertainty might reasonably be supposed to be. If the nervous system delays before action, a higher degree of reliability can be obtained by averaging successive messages in any particular pathway. There are two ways in which this can be done. On the one hand, a fixed time could be set in advance, before any stimulus is received. On the other hand, the mechanism could conceivably work by accumulating evidence until there is sufficient in favor of one alternative rather than the other. The first of these possibilities is mathematically the most tractable, when there are more than two alternatives; and it has been shown that it will predict the general logarithmic relationship between reaction time and the number of alternative reactions (*17*).

Unfortunately, this is almost certainly not the mechanism which the nervous system actually employs, because we can, in one and the same experiment, use probable and improbable signals, and we then find that the reaction time to the probable signal is considerably faster than that to the improbable one. If the time taken for the decision was laid down in advance of any signal's arriving, this could hardly be the case. The second type of mechanism, unhappily, is much harder to analyze mathematically, for cases in which there are more than two possible signals: but there are certain features which such a mechanism would have and which human performance seems to show. For example, the mistakes made by such a mechanism would usually take the form of making probable responses to improbable stimuli, rather than vice versa, and this is indeed what people usually do (*18*). A good deal of research effort is at present going into finding ways of checking whether this hypothetical mechanism is really the way in which the nervous system operates in performing choice reactions.

Conclusions

The foregoing discussion has left out of account a large number of features of information processing which are of much current interest. These include, for example, the possible distinction between short-term and long-term memory processes, or the extent and fashion in which changes in general physiological state due to drugs or other stresses may modify the processes. The particular problems discussed have been chosen to emphasize the ways in which the nervous system is forced to economize on mechanism and to compensate for unreliability. Both these principles have modified our attitude towards the brain: for it was once easy and natural to think of the nervous system as resembling an old-fashioned manual telephone exchange, in which each incoming message is connected to an outgoing pathway, completely determinately and by its own private cord, quite independent of any other connections that might exist. Such an analogy has now been out of date for many years, and we must think rather of a mechanism which cannot deal with all the incoming messages and which therefore selects among them.

Above all it is becoming increasingly likely that central processes inside the nervous system contain an appreciable amount of unreliability, and that this is taken into account in the way the nervous system operates. This latter development is particularly significant, because it suggests a parallel with statistical decisions, which take into account gains and losses. Thus it may afford a place in the study of information processing for motivational factors of a sort which have traditionally been considered more by intuitive and clinical psychology than by those abstract and instrumental investigators concerned with reaction time and with sensory thresholds. As yet, even the bonds between physiology, artificial intelligence, and experimental psychology are regrettably weak; and connections with clinical psychology are not yet on the horizon. Nevertheless, those connections will ultimately need to be made, and it is gratifying that recent studies of information processing are beginning to find a place for motivational variables such as gain and loss.

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NEWS AND COMMENT

1965 Nobel Laureates in Medicine or Physiology

The award of the Nobel prize for physiology or medicine to André Lwoff, Jacques Monod, and François Jacob, of the Institut Pasteur of Paris, finally ends the 30-year period during which no Nobel prize was given to a French scientist, a period that began when Frédéric and Irène Joliot-Curie received the chemistry prize in 1935. This apparent lack of highest recognition of its leading scientists had become a matter of some public concern in France, and it is not without irony that just these three men should have been chosen to break the prizeless spell. For, while Lwoff, Monod, and Jacob had long been recognized abroad as among the world's leading modern biologists, they remained virtually unknown and without influence on scientific affairs in their own country. Both the Royal Society of London and the United States National Academy of Sciences elected André Lwoff to foreign membership years ago; but the French Academy of Sciences has not yet seen fit to include him in its ranks.

The present generation of biologists generally thinks of André Lwoff in connection with the work for which he was honored by this prize: his demonstration in 1950 that lysogenic bacteria perpetuate the capacity to produce virus in the form of the noninfective *prophage* and his discovery (in collaboration with his disciples Siminovitch and Kjeldgaard) that the prophage can be induced at will to produce infective virus, by ultraviolet light. It may have been forgotten, however, that Lwoff's study of lysogenic bacteria was only the third major incident in a career which had already gained him international fame. Lwoff began study of the morphogenesis of protozoa in the 1920's, work that culminated in the discovery of extranuclear inheritance in these organisms. Those studies established Lwoff as one of the leading protozoologists of his time. In the 1930's Lwoff turned to the nutrition of protozoa and pioneered the development of chemically defined media for their growth. In the course of this work he identified vitamins as microbial growth factors and, in a famous paper published in 1936 in collaboration with his wife, Marguerite, showed that vitamins function as coenzymes. This established Lwoff as one of the great figures in the development of nutrition as a science.

In 1941 Lwoff published his classic and influential treatise *l'Évolution Physiologique*, in which he developed the "pessimistic" thesis of biochemical evolution by progressive losses of biosynthetic capacity.

While working at the Institut Pasteur in the 1930's, Lwoff became the friend of Emanuel Wollman, one of the early students of lysogenic bacteria, who was later killed in a Nazi concentration camp. After the war, Lwoff decided to carry on Wollman's work, at a time when lysogeny was held in the lowest possible esteem by the then-nascent school of modern American bacterial virologists. But Lwoff's indubitable proof that lysogenic bacteria *do* perpetuate viruses as part of their heriditary constitution not only made lysogeny once more a respectable endeavor but also changed radically the views on the natural relation of viruses to their host cells, from inexorable morbidity to facultative peaceful coexistence.

Jacques Monod began his scientific career in the 1930's, also, as it happens, by working on protozoa. It cannot be said, however, that this work gained *him* any fame. In fact, Monod then still thought of quitting science altogether and devoting himself entirely to the cello, which he still plays with professional competence. But Monod decided to give biology another try and turned his attention to bacterial growth. This work, in which Monod developed quantitative methods and principles of growth of bacterial cultures which are now standard operating procedure in all of bacterial physiology, was published in 1941 as his doctoral thesis, "Recherches sur la Croissance Bactérienne." Upon the fall of France, Monod joined the French Resistance movement and, in time, commanded one of its underground military units. After the liberation, Monod was assimilated into the regular French Army and finally wound up in the military government of occupied Germany. In 1946 he left the army and returned to Paris to join Lwoffs Department of Microbial Physiology at the Institut Pasteur, where he began study of the synthesis of the inducible bacterial enzyme β-galactosidase. Whereas at that time such men as Max Delbrück, Salvador Luria, and