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EPILOGUE

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Warren McCulloch was a remarkable man. In his professional life he was at one time or another physician, neurologist, psychiatrist, neurophysiologist, and one of the first automata theorists and cyberneticians. Together with Walter Pitts he laid the foundations of a large part of modern automata theory, and of artificial intelligence research. In addition he was a philosopher, poet, and teller of tall tales. He wrote some two hundred or more papers, and made a profound contribution to the way we now think about how brains work, about machine intelligence, and about what is commonly called "the mind-body problem".

McCulloch's papers reflect his breadth of interest. They range from the nature of epileptic seizures, through the use of strychnine as a method of discovering anatomical connections and the consequent functional organization of the cortex, the nature of schizophrenia, the functioning of the cerebellum and basal ganglia, electrophysiology of sources and sinks of ionic currents, presynaptic inhibition in the spinal cord, the functional and structural organization of the frog retina and of the retino-tectal projection, to the theory of finite-state automata, cybernetics and information processing, reliable neuronal nets from unreliable elements, the functioning of the brain-stem reticular formation, regenerative neuronal circuits embodying logical relations, and finally to a series of essays on epistemology and the nature of the mind.

The early papers deal mainly with seizures and with the effects of strychnine. A good summary of this work is to be found in the paper, *Mechanism for the Spread of Epileptic Activation of the Brain* (1) which appeared in the first issue of the journal, Electroencephalography and Clinical Neurophysiology in 1949. In this paper McCulloch discusses the notion that the (local) spread of cortical activity depends upon:

> ...the statistical probabilities of connection [and that] the velocity of propagation of the [surface negative] wave is a function of threshold: for the propagation depends upon getting enough impulses impingent on the next area to increase its activity above the mean threshold of the fibers there.

He also discusses the surface-positive wave generated by the (non-local) spread of activity from one cortical region to another by way of action potentials in myelinated fibers; and also the spread of "suppression" and "depression." It was the surface-positive wave activity which de Barenne and McCulloch demonstrated to be markedly affected by the topical application of strychnine. They were thus able to map cortico-cortical connections. Contemporary methods use vital dyes such as Horseradish peroxidase or Tritiated amino acids to trace pathways. It is still an open question as to their efficacy compared with strychnine neuronography, as a marker of functionally significant pathways.

Another representative paper is that one by Meduna and McCulloch entitled, *The Modern Concept of Schizophrenia* (2) published in The Medical Clinics of North America in 1945. In this paper Meduna and McCulloch distinguish between true schizophrenia, and what they term "oneirophrenia". According to Bleuler, true schizophrenia is characterized by three main symptoms: specific disturbances of associations of ideas, and of "affectivity", and no primary sensory disturbances. Meduna and McCulloch distinguish this syndrome from oneirophrenia, in which there are sensory disturbances evidenced by illusions, confusions, disorientation; loss of contact, true amnesia, benign stupor; true hallucinosis; inexplicable and involuntary thoughts and feelings inducing dread; weird and frenzied delusions.

McCulloch always felt that the chief causes of oneirophrenia were metabolic, perhaps a defect in carbohydrate metabolism, and he returned to this topic on numerous occasions. This paper is also of interest in that it is perhaps one of the earliest indications of McCulloch's growing antipathy to analytical psychiatry.

McCulloch also had a continued interest in the control of posture and motion. He published a series of papers with Snider, Magoun and others on the action of the cerebellum and basal ganglia, and with Lettvin, Wall, Pitts and others on spinal motor systems. In one of his last papers, *Control of Posture and Motion* (3) [210] published in Biomechanics in 1969, there is a clear and succinct description of cerebellar function.

> Now the business of the cerebellum can be simply stated. It must bring to rest at the right place and time whatever is put in motion...[it] is at least an interval clock... once one has such an interval clock that can be tapped at all points, one has an ideal autocorrelation to bring signals up out of noise.

His collaboration with Lettvin, Wall and Pitts, initiated in Chicago, continued when the group moved to M.I.T. in 1952. For a few years their principal goal was to develop a theory of synaptic transmission based on simple electrical principles. A good example of this is in the paper, *Reflex Inhibition by Dorsal Root Interaction* (4) by Howland, Lettvin, McCulloch, Pitts and Wall, published in J. Neurophysiology in 1955. In this paper Howland, *et al* introduced a novel current source density analysis to characterize interactions among spinal afferents: with this they discovered what is now called "pre-synaptic inhibition", the inhibition of one pre-synaptic fiber by another. This proved to be one of the more important contributions of the group to neurophysiology.

A much more important contribution however, was contained in the paper, *What the Frog's Eye Tells the Frog's Brain* (5), published in Proc. IRE in 1959. In this paper Lettvin, *et al* introduced a very important concept into sensory physiology, that of "feature detectors." Earlier work of Hartline, Kuffler and Barlow has established that retinal neurons respond strongly to spots of light, particularly against a contrasting background. Lettvin, *et al* argued however, that what is important is not:

> ...that the eye mainly senses light, whose local distribution is transmitted to the brain in a kind of copy by a mosaic of impulses... [but] that the nervous apparatus in the eye is itself devoted to detecting certain patterns of light and their changes, corresponding to particular relations in the physical world.

With this in mind they found that in the Frog retina there are four separate operations performed on the optical image, each transmitted by a different group of fibers to the optic tectum. These operations were feature detecting, namely, sustained contrast, net convexity, moving edge and net dimming detection. As Lettvin, *et al* put it so well:

> [These] operations... have much more the flavor of perception than of sensation... By transforming the image from a space of simple discrete points to a congruent space where each equivalent point is described by the intersection of particular qualities in its neighborhood, we can then give the image in terms of distributions of combinations of those qualities. In short every point is seen in definite contexts. The character of these contexts, genetically built in, is the physiological synthetic *a priori*.

Such ideas, then radically new in neurophysiology, have greatly influenced the course of much of the work done in sensory physiology, and also in research on machine pattern recognition. It has proved to be the case that the retinas of higher vertebrates such as cats and primates are less, rather than more specialized, so far as the analysis of the visual image is concerned, and that as Hubel and Wiesel have so clearly shown, it is the business of the visual cortex and beyond to carry out context dependent feature detection and pattern recognition. In this writer's opinion however, there is still room for Lettvin, *et al's* synthetic *a priori* in the Cat and Primate cortex, but at a level of organization not yet uncovered by current physiological experimentation.

There is yet another aspect of *What the Frog's Eye Tells the Frog's Brain* that is of note. This concerns what is sometimes termed "neuronal specificity", meaning the precision and reliability with which differing elements of the nervous system are interconnected. Lettvin, *et al* noted that although the optic nerve fibers terminate in the optic nerve:

> ...in an orderly way such that the termini exhibit a continuous map of the retina... [and indeed such that] the four operational groups of fibers terminate in four separate layers of terminals, each layer exhibiting a continuous map of the retina... and all four maps in registration... the optic nerve fibers are all disordered in position through the [optic] nerve.

They were therefore among the first to discover the complexity of Frog retino-tectal maps, and the need for some reorganization of retinal fibers upon their reaching the tectum. They also confirmed

Sperry's earlier conclusions concerning the presence of "chemoaffinity": they severed the optic nerve and found that the four maps reformed in register as before, i.e., "that the fibers grew back to the regions where they originally terminated in mapping the retina...[and that] we also found a restoration of the four layers with no error or mixing". These findings have since been reconfirmed many times, and the subject of specificity and chemoaffinity is now one in which there is a great deal of activity. Lettvin, *et al's* contribution to this remains significant.

Of course McCulloch's interest in the synthetic *a priori* of Kantian philosophy, and in related epistemological problems, predated the publication of *What the Frog's Eye Tells the Frog's Brain* by some 40 years. He had always been interested in such problems. In one of his later essays, *What Is a Number That a Man May Know It, and a Man, That He May Know a Number?* (6) published in the General Semantics Bulletin in 1961, he relates how he tried in 1919 to construct a logic of transitive verbs, and in 1923, a logic of propositions.

> My object, as a psychologist, was to invent a least psychic event, or "psychon", that would have the following properties: First, it was to be so simple an event that it either happened or else it did not happen. Second, it was to happen only if its bound cause had happened - shades of Duns Scotus! - that is, it was to imply its temporal antecedent. Third, it was to propose this to subsequent psychons. Fourth, these were to be compounded to produce the equivalents of more complicated propositions concerning their antecedents... In 1921 it dawned on me that these events might be regarded as all-or-none impulses of neurons, combined by convergence upon the next neuron to yield complexes of propositional events.

It was not until 1942 however, that McCulloch succeeded in constructing such a logic in collaboration with Walter Pitts. Their first paper, *A Logical Calculus of the Ideas Immanent in Nervous Activity* (7), published in the Bulletin of Mathematical Biophysics in 1943 is remarkable in many respects. It is best appreciated, however, within the *zeitgeist* of the epoch when it was written. As Papert has so ably written in his introduction to *Embodiments of Mind*, 1943 was a seminal year for the development of the sciences of the mind. Craik's monograph, *The Nature of Explanation*, and the paper, *Behavior, Purpose and Teleology* by Wiener, Rosenbleuth and

Bigelow, were also published in 1943. As Papert has noted "The common feature [of these publications] is their recognition that the laws governing the embodiment of mind should be sought among the laws governing information rather than energy or matter". The paper by McCulloch and Pitts certainly falls within this framework: it deals with the embodiment problem in terms of the properties of nets of formalized neurons, or *neuronal nets*, by showing that a very large class of hypotheses about brain mechanisms, namely *all* hypotheses which can be stated in *finite* terms, can be embodied in finite neuronal nets. As McCulloch and Pitts asserted, it is easily shown that:

> ...every net, if furnished with a tape, scanners connected to afferents, and suitable efferents to perform the necessary motor operations, can compute only such numbers as can a Turing machine...[and] that each of the latter numbers can be computed by such a net... and that nets with circles [feedback loops] can compute, without scanners and a tape, some of the numbers the [Turing] machine can, but no others and not all of them.

Thus McCulloch-Pitts nets, as they are sometimes called, are *finite state automata*, in which the present state, i.e., the pattern of activation of all neurons in the net, together with the afferent stimulus, determines the next state. Such nets embody the logic of propositions, as McCulloch wished, and permit the framing of sharp hypotheses as to the nature of brain mechanisms, in a form equivalent to computer programs.

This was a remarkable achievement. It established, once and for all, the validity of making formal models of brain mechanisms, if not their veridicality. It also established the possibility of a rigorous theory of mind, in that neuronal nets with circles can exhibit purposive behavior, or as McCulloch and Pitts put it:

> ...both the formal and the final aspects of that activity which we are wont to call mental are rigorously deducible from present neurophysiology... [and] that in [imaginable nets]... "Mind" no longer "goes more ghostly than a ghost".

In the years since the publication of *A Logical Calculus of the Ideas Immanent in Nervous Activity* thousands of papers have been published on neuronal net models for a variety of brain mechanisms, and even a few which embodied theories of mental activity.

The latter have not been particularly successful, largely because of the lack of an adequate theoretical epistemology. The modeling of brain mechanisms however, has flourished, although the results to date have been somewhat disappointing, largely because most brain mechanisms are very complicated. A notable early attempt in this direction however, was Pitts' and McCulloch's own paper, *How We Know Universals: the Perception of Auditory and Visual Forms* (8), published in the Bulletin of Mathematical Biophysics in 1947. In this paper Pitts and McCulloch discussed the problem of form recognition. They proposed two mechanisms which combined to secure scale invariant recognition: the first subjected the cortical image of any stimulus pattern to a group of dilatations and then averaged over the group, the second centered any image in a standard position. The resultant excitation is clearly invariant under the group of dilatations, and under two-dimensional translations. Pitts and McCulloch proposed that the visual cortex "scanned" the visual image and computed the average of such a scan, and that the superior colliculus centered the image. They suggested that the well-known 10Hz "alpha rhythm" seen in electroencephalograms of the occipital lobe, was a signal generated by the scanning process.

Although it now seems likely that the superior colliculus indeed plays a role in centering visual images, it appears not to be the case that size invariance is secured by the process proposed by Pitts and McCulloch. However there are many aspects of this paper which remain of interest today, particularly their insistence that there is more to perception than the mere topographic imaging of a figure on the visual cortex, or there are what are now called "grandmother cells", specialized for the detecting of images of grandmother!

> It is worth observing... that the group-invariant spatio-temporal distribution of excitations which represents a figure need not resemble it in any simple way... This point is especially to be taken against the Gestalt psychologists, who will not conceive a figure being known save by depicting it topographically on neuronal mosaics, and against the neurologists of the school of Hughlings Jackson, who must have it fed to some specialized neuron whose business is, say, the reading of squares. That language in which information is communicated to the homunculus who sits always beyond any incomplete analysis of sensory mechanisms and before

> any analysis of motor ones neither needs to be nor is apt to be built on the plan of those languages men use toward one another.

This point of view, of course, permeates *What the Frog's Eye Tells the Frog's Brain*, but there are still many contemporary neurophysiologists who follow Hughlings Jackson's dictum.

In the late 1950's and early 1960's McCulloch turned to another theoretical topic: the reliability of biological computation. In his work with Pitts, McCulloch had always considered it important to construct neuronal nets:

> ...so that their principal function is little perturbed by small perturbations in excitation, threshold, or detail of connection within the same neighborhood. Genes can only determine statistical order, and original chaos must reign over nets that learn, for learning builds new order according to a law of use.

Together with Pitts and H.D. Landahl he had also noted that a statistical representation of neuronal net activities could be obtained by considering, not the all-or-none nature of the individual action potential, but the much smoother changes in the mean firing frequency of formal neurons. In such a representation, the Boolean functions "and", "or" and "not" are replaced by the arithmetical operations "x", "+" and "1-", respectively. But it was his conversations with John von Neumann which led him to consider how to construct neuronal nets that were logically stable, i.e., that would compute a Boolean function invariant to changes of the thresholds of all the neurons in the net. The outcome of this work is best seen in the work of two of his research assistants, S. Winograd and this author, who were able to demonstrate the relation of such problems to Information and Coding Theory, in particular to Shannon's famous noisy channel coding theorem. Neuronal nets that embody error-correcting codes are much more elaborate and complex than those lacking such capabilities. As McCulloch put it in his essay, *What's in the Brain That Ink May Character?* presented at the International Congress for Logic, Methodology, and Philosophy of Science in 1964,

> ...it is clear that, for an information-theoretic capacity in computation in the presence of noise, the logic has to be multiple truth-valued, and the constructions require, for coding without fatal multiplication of unreliable components, not threshold elements,

but those capable of computing any Boolean function of large numbers of inputs.

In the years since 1964 there have been two developments in the theory of neuronal nets, of interest for the reliability problem. One was the development of methods for dealing, not with the intermittent failures of formal neurons presumed above, but with the permanent failures caused by neuronal death. The other was the realization that coping with ambiguities of stimulus representation was probably a bigger problem than dealing with internal fluctuations. Both these problems were solved in the 1960's through the work of W.H. Pierce, P.H. Greene, D.C Marr and others, with the construction of neuronal nets similar to those introduced by Winograd and Cowan, but containing modifiable synapses. The last decade has seen a proliferation of theories of learning and memory which utilize neuronal nets with modifiable synapses in some form or another. McCulloch anticipated many of these developments, but he also sounded a cautionary note. Thus in his monograph *Finality and Form* (9) published in the American Lecture Series, Springfield, Ill. in 1952, he writes:

> We want a theory of learning that will work when the number of neurons is large, and the net random. Similar problems arise in the physics of magnetizing a bar of steel. It starts as a large number of little magnets left pointing hither and thither by chance. Each of these little magnets can be turned about by an applied magnetic force. The little magnets near a particular magnet contribute to the forces acting on it. The configuration of all the applied forces serves as a pattern for the configuration of the little magnets, any local figure in the forces giving a local structure. Finally the little magnets stay in the positions they had at the time the forces cease to be applied. To see how much alike magnetizing and learning may be, we may write the analogies in parallel order: the random net composed of neurons with the initial unmagnetized bar; the formation of synapses with the magnetization; excitation with the applied field; concomitant activity in nearly connected neurons making for structural changes with the mutual influence of neighboring magnets; enduring things that potentiate figures of stimulation and the consequent stimulating of the net with the magnetic induction; and finally, the abiding of those links which were last used as we came to our goals and the reflexive or appetitive activity to its end with the final state of permanent magnetism in the bar...
>
> What troubles my dreams is this: that when it is done, it will not be enough... I fear that the nervous system that learns as iron is magnetized, while it will give us a next number or a new experi-

> ment, may not give us the law of formation of the series - say the idea, the cardinals or the primes - or the hypothesis - say the law of gravitation, or the second law of thermodynamics. To use an idea is a finite act, which begins and ends in time; and when it occurs, it must not merely give the next number or experiment - for an infinite number of ideas or hypotheses give the same next. It must set the law forth in signs of some sort. There is no other way to know that the law exists. In a finite net we seek a kind of finite action that can be repeated as often as desired, and can construct and recognize notions proper to the next. I know of nothing but circular paths that embody the possibility of such actions... Each circuit has embodied an idea of a kind not to be had without it. If these circuits can be engendered by learning in a random net, and that learning can be described in much the same manner as the magnetizing of a bar of steel, we may be able to picture to ourselves how a natural nervous system can come to have notions of the cardinals or hypotheses like the laws of mechanics.

This passage illustrates very well McCulloch's rationalist quest for truth. He often used to say, "If it's true it works!", rather than, "If it works it's true!". Most contemporary neuronal modellers have lost sight of this distinction. McCulloch was very concerned with the logic of thinking. He distinguished between *deduction*: rule, case under rule, therefore fact; *induction*: case, fact, therefore rule; and *abduction*: rule, fact, therefore case under rule. It is abduction that leads to new hypotheses. In these terms, McCulloch-Pitts nets with fixed synapses are deductive, whereas those with modifiable synapses are inductive or "habit-taking". In his later work McCulloch was much concerned with abductive machinery. Thus in his essay, *What's in the Brain That Ink May Character*, he writes:

> The next step [beyond deducing and habit-taking]...would obviously be to postulate a process of concept formation. This is the very leap from weighing probabilities to propounding hypotheses... it requires a succession of subordinate insights organized at successive superordinate levels or types... what Hughlings Jackson called "propositionalizing". This certainly cannot be left to variation and selection as an evolutionary process starting from chaos or a random net. That would be too slow.

McCulloch proposed that the brain-stem reticular formation contains abductive machinery.

> In general, you may think of it as a computer to any part of which come signals from many parts of the body and from other parts of

> the brain and spinal cord... Its business, given its knowledge of the state of the whole organism and of the world impingent upon it, is to decide whether the given fact is a case under one or another rule. It must decide for the whole organism whether the rule is one requiring fighting, fleeing, eating, sleeping, etc.....Of necessity, the system must enjoy a redundancy of potential command in which the possession of the necessary urgent information constitutes authority in that part possessing the information.

McCulloch wrote a series of papers with W. Kilmer, J. Blum and others, on the structure and functioning of the reticular formation, but he was not satisfied with the results achieved. He felt keenly the lack of an adequate mathematical theory of the dynamics of neuronal oscillators. Today we have such a theory, and it is conceivable that a theory of the reticular formation can be formulated along the lines outlined by McCulloch. Whether it would furnish the necessary abductive machinery is moot. McCulloch was somewhat pessimistic about the outcome, largely because of the lack of an adequate calculus of triadic relations. He felt that in all problems of biological communication, for example, in those involving the reticular formation:

> ...we are dealing with a triad of Sender, Signal and Receiver, and with the Stoic triad: A means B to C. The signal means to the receiver what the sender intended.

and that the necessary logic to deal with such problems was non-existent. His last theoretical studies were all concerned with this problem, in the form of a study of nets with loops, with R. Moreno-Diza and J.L.S. Da Fonseca. It is fair to say that these problems remain largely unsolved.

McCulloch also wrote a number of essays, beginning with *Why the Mind is in the Head* (10) which appeared in Cerebral Mechanisms in Behavior, the Hixon Symposium of 1951; and ending with *This Superfluity of Naughtiness* (11), an unpublished essay presented at a symposium on The Moral and Esthetic Structure of Human Adaptation, organized by the Wenner-Gren Foundation in 1969. These essays are a remarkable mixture of philosophy and science. In them McCulloch repeatedly expresses his rationalism; his disdain for theories of the mind which deal only with *passage* and *extension*, the "doings" and "havings" of things; and his contempt for Freudian psychoanalytic theory. In *Through the Den of the Metaphysician* (12) published in French in Thales, 7 in 1951, for example, McCulloch starts out by writing:

> Our adventure is actually a great heresy. We are about to conceive of the knower as a computing machine.

He reiterates this in "*Mysterium Iniquitatis* of Sinful Man Aspiring Into the Place of God" (13) which appeared in the Scientific Monthly, 80, 1, in 1955:

> Russell has already noted that the explanation of mind has become more materialistic only as our matter has become less material... Everything we learn of organisms leads us to conclude not merely that they are analogous to machines but that they are machines.

This notion is the source of McCulloch's epistemology. In *Through the Den of the Metaphysician* he asserts:

> ...let us ask whether a knower so conceived is capable of constructing the physics of the world which includes himself. But, in doing so, let us be perfectly frank to admit that causality [any law of necessary connection between events] is a superstition...[and that] our thought does not imply our action, but... only intends it. Per force we distinguish between futurity and intention. Our notion of our wills has... arisen from this enforced distinction, and its perennially questioned "freedom" presumably means no more than that we can distinguish between what we intend and some intervention in our action. If I shall do what I will do, then my will is free.

In *Towards Some Circuitry of Ethical Robots or an Observational Science of the Genesis of Social Evaluation in the Mind-Like Behavior of Artifacts* (14), published in Acta Biotheoretica, XI in 1956, he proposes to investigate what machines, by cooperation and competition, can constitute a society where their conduct becomes self-disciplined in a way that serves the ends created by their association.

In *Finality and Form in Nervous Activity*, (loc. cit) he asserts:

> ...that problems of the theory of knowledge and of value... can be stated and solved only in terms of the anatomy and physiology of the nervous system. In those terms, we are inquiring into the *a priori* forms and limitations of knowing and willing determined by

> the structure of the nervous system and by the mode of action of its elements.

The reader will find in McCulloch's essays many examples of similar type, all reiterating the theme that a true theory of knowledge must be founded on an understanding of how the brain works. It was McCulloch's opinion that Freudian psychoanalytic theories were so patently wrong for such a goal, as to be useless. In *The Past of a Delusion* (15), a written version of a lecture given to the Chicago Literary Club in 1953, he writes:

> Dependence of the data on the theory separates psychoanalysis from all true sciences... Interpretations of chaotic dreams are still controlled by theory, and that theory was in the head of Freud. Change this, and you have changed the method and the data. This is the curse of all attempts to understand things social. They are essentially sharing. What we seek to understand is coupled back through us, so that we ourselves change the thing we seek to understand. When this coupling grows very close it is, in Freudian lingo, called "transference". Freud himself came to attribute to transference what therapeutic value lay in analysis. The pragmatic test of truth, "Analysis is true because it works"...stands here accused of folly in full daylight. Science must have data not vitiated by our theory ... The Freudian scheme is a tissue of unverified and often unverifiable hypotheses, all oversimplified... All our hypotheses are of a kind that do require, if they be right, that we shall find this going on now, here; and that, then, there: whereas Freud's notions fail to locate in space and time his hypothetical Id, Unconscious, Ego, Super-Ego, or to predict what they will look like in the brain...

McCulloch's answer to psychoanalysis was, as always:

> To find out how brains work, and so to help those who have need of a physician.

McCulloch's last essay, *This Superfluity of Naughtiness*, written shortly before he died in 1969, is a distillation of all that concerned him during his working lifetime. He felt keenly the breakdown of the old order, and worried about what was going to replace it, and to inspire the young. He felt that:

> Biology is the most likely source of inspiration, provided it is not reduced to the Nothing-butery of biophysics.

Here again is the call to arms, to defend idea and intention in the quest for the nature of mind and meaning. Progress on this front to date, has been slow. However, recent developments in studies of Machine Intelligence indicate that the path blazed by McCulloch is still visible. It is to be hoped that this edition of McCulloch's collected papers will further stimulate a new generation of theorists of the brain to begin to think about such fundamental questions.

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