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From Logical Neurons to Poetic Embodiments of Mind: Warren S. McCulloch's Project in Neuroscience

Argument

After more than half a century of eclipse, the mind (in contradistinction to brain and behavior) emerged in the 1950s as a legitimate object of experimental and quantitative research in natural science. This paper argues that the neural nets project of Warren S. McCulloch, in frequent collaboration with Walter Pitts, spearheaded this cognitivist turn in the 1940s. Viewing the project as a spiritual and poetic quest for the transcendental logos, as well as a culturally situated epistemology, the paper focuses on McCulloch's and Pitts' efforts of logical modeling of the mind and on the social conditions that shaped that mission,

From McCulloch's "experimental epistemology," the mind – purposes and ideas – emerged out of the regularities of neuronal interactions, or nets. That science of mind thus became a science of signals based on binary logic with clearly defined units of perception and precise rules of formation and transformation for representing mental states. Aimed at bridging the gulf between body and mind (matter and form) and the technical gulf between things man-made and things begotten, neural nets also laid the foundation for the field of artificial intelligence.

Thus this paper also situates McCulloch's work within a larger historical trend, when cybernetics, information theory, systems theories, and electronic computers were coalescing into a new science of communication and control with enormous potential for industrial automation and military power in the Cold War era. McCulloch's modeling the mind as a system of command and control contributed to the actualization of this potential.

We build our castles in the air,
And from the air they tumble down
Unless we carry them up there
Until they crack the pate they crown.
And we must lug them everywhere,
From garden walk to crowded town
We build our castles in the air,
And from the air they tumble down
And lucky, if when sere and brown,
Before our eyes too lofty stare,
We scope with life and pate, though bare,
On which to plant an honest frown.
We build our castles in the air,
And from the air they tumble down.

Warren S. McCulloch[1]

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1 Of McCulloch's literary work only two thin volumes, *One Word After Another* (1945) and *The Natural Fit* (1959), have been published. Most of his poetic output was unpublished and is deposited at the American Philosophical Society (hereafter APS) in the McCulloch Papers, BM 139. The poem, originally published in *The Natural Fit,* is quoted after McCulloch 1989, vol. 3, 917. For commentary on his poetry, see Vasalis 1989.

Introduction

In 1943, at the height of World War II, Warren S. McCulloch and Walter Pitts wrote their first joint article bearing the enigmatic title, "A Logical Calculus of the Ideas Immanent in Nervous Activity". The conjunction of logic, neurology, and poetics produced a nearly incomprehensible abstraction (a classic often cited but seldom read) that lay a foundation for several new areas of knowledge: cybernetics, computer science, cognitive science, artificial intelligence, and most specifically, neural nets; areas which contributed substantially to the making of modern neuroscience. But the principal significance of the McCulloch-Pitts project inheres in its cognitive turn, in bringing the psyche back into the laboratory: into neurophysiology, where mind had acquired a ghostly status; into psychology, where it had been black-boxed by behaviorists; and into psychiatry dominated by Freudian, qualitative representations. Within McCulloch's and Pitts' "experimental epistemology," the mind became a legitimate, even esteemed object of study in the 1940s, '50s, and '60s, an object of quantitative representations that bore novel implications for the age-old queries about the relations between mind and body, the natural vs. the artificial, and for automated military technologies of the postwar era.[2]

Yet it is not "the mind" as an eternal and immutable object which McCulloch and Pitts brought into experimental quantitative research in the 1940s. It was not the same mind that, as the epitome of human consciousness and identity, had been an object of scientific intrigue since antiquity. Though some features and images have indeed persisted through the ages, the soul, psyche, anima, and mind have always been suffused with historically-situated spiritual symbolisms and cultural meanings. And as such, in each epoch, the mind was reconstituted anew as an object of study within new discourses and hence invested with its own historicity, even when, by the beginning of the twentieth century, it was being expunged from the laboratory (see e.g. Smith 2001, this volume). Thus the McCulloch-Pitts notion of mind as neural nets was reconstituted within a new space of representation – the information discourse – which emerged in the 1940s in the United States and Europe. That discourse, which crystallized around the war-born fields of cybernetics, the mathematical theory of communication, digital computing, and control systems, would reconfigure representations of life and society as systems of decisions and signals; it was a technoepistemic transformation across the disciplinary landscape and the culture at large (on the information discourse, see Kay 1995; Kay 1997; and Kay 2000, ch.1).

The McCulloch-Pitts project belongs to this cognitive and cultural transformation. Three major leaps were taken in the 1943 McCulloch-Pitts article: first, that ideas and mind were a proper object of quantitative study; second, that binary logic was the means with which to understand the brain and mental activity; third, that these logical principles were embodied in the brain and its elemental components, the binary neurons (in their "on-off" mode of action). Mind and ideas thus emerged out of the interactions of neurons, out of the logic of neural nets. Clearly, McCulloch's goals were unrealistic; his premises and approaches grossly oversimplified – perhaps "castles in the air" to use his own phrase. But these poetic distillations formed a powerful model, introducing representations of mind as a non-localized, topologically-fluid, emergent entity, an information system that merged matter and form, medium and message (Varela, Thomson, and Rosch 1991, ch.3).

2 McCulloch's references to "experimental epistemology" are ubiquitous in his writings, see for example "Preface" to McCulloch 1965. See also Lettvin 1989d. On the cognitivist turn, see Gardner 1985, ch. 2; and Varela, Thompson, and Rosch 1991, ch. 3.

And their project was not merely an application of mathematical models to physiological and mental phenomena – such practices were certainly not novel. Rather, the novelty in their notion of mind lay in equating the operations of reason with those of binary-logic neurons. As such, that mind stood for the quintessential Platonic logos, the embodiment of Kant's synthetic *a priori*, and the site of command and control. Granted, McCulloch's conceptual tools – neurophysiological data, psychiatric knowledge, philosophical theories, propositional logic, Boolean algebra, electrical engineering, theological and military imagery, and even aspects of information theory – dated back to earlier periods. But the particular configurations of these tools and the premises governing their use bore the unmistakable marks of a new, postindustrial episteme: an emergent technoculture of communication, control, and simulation; the concepts produced within its regimes of signification are evidenced not only in McCulloch's works but in those of his colleagues and other contemporary adventurers in science (see Schaffer 1999; on the relation between mathematics and neuroscience, see Changeux and Connes 1995).

This paper examines the McCulloch-Pitts cognitive turn as a culturally-situated epistemology, and their concept of mind – normal and aberrant – as constituted within new discursive practices. It does so by focusing primarily on their work in the 1940s at the University of Illinois. Of course, important elements of the neural-nets concept were already present in McCulloch's work in the 1920s and '30s (primarily at Yale), and its maturation – with its deep connections to military-industrial projects – took place at MIT in the 1950s and '60s. Yet it is the conceptualization of the 1943 paper, its reception, and its elaborations into later publications of the 1940s, which are essential for understanding the cognitive scope and limits of the McCulloch-Pitts neural nets project, its discursive significance and social valences at the threshold of the age of information.

I. Logical Neurons as Embodiments of Mind

What is mind? Well before McCulloch, answers to this question have lured and evaded philosophers and scientists through the centuries; and among earlier attempts – notably Gottfried Wilhelm Leibniz and Charles Babbage – conceptualizations of the mind as a deductive machine and a calculating device have implicitly equated human reason with mathematical operations. And so it was for the young McCulloch. When asked by his philosophy professor, "Warren, what are thee going to do?" McCulloch responded, "I have no idea; but there is one question I would like to answer: What is number, that a man may know it, and a man, that he may know a number?" His professor smiled and said, "Friend thee will be busy as long a thee lives." Indeed, McCulloch would spend his entire life answering this question. A product of devout spiritual (Episcopalian) and patriotic upbringing, McCulloch's quest was propelled by twin passions: The logos as God's immanence and His bequest to Man, and the military as an embodiment of order (APS, McCulloch Papers, BM 139, no. 2., McCulloch u.d., ca. 1960s, 1).[3]

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3 See also McCulloch 1960. On his enthusiasm for the military, see Rook McCulloch 1989. On the nervous system as command control, see McCulloch 1966; Kilmer and McCulloch 1969 and McCulloch 1989, vol. 4, 1306 and 1322-1332. Published and archival sources on McCulloch are abundant. In addition to his own collected samplings of his writings (*Einbodiment of Mind*), and the four volumes of his collected works, which include commentaries by his colleagues and friends (especially Jerome Lettvin), the McCulloch Papers (APS) are a rich record of correspondence and professional activities, including collaborations with the military (no. 1), lectures and papers (no. 2).

McCulloch came to neural nets through a circuitous path: via theology and philosophy, mathematics, psychology, medicine, and neuropsychiatry. During the 1930s, before moving to the University of Illinois to head the Department of Psychiatry and the Illinois Neuropsychiatric Institute (1941), he worked at Yale University with his Dutch mentor, Dusser de Barrenne, who as the last link in the neo-Kantian physiological tradition, imparted McCulloch with the conviction in the primacy of the physiological *a priori*: that Kant's synthetic *a priori* – the perceptual manifold through which raw sensory data is sorted – could be accessed through the hard-wiring of the nervous system (Kant 1965, especially Introduction and Part I).[4]

Using de Barrenne's method of local strychninization of the brain (of cats and monkeys) they identified central structures of the cerebral cortex. Combined with electrical recordings, these studies led to the production of maps of circuit action from which a wiring diagram could be deduced. This work proved to McCulloch that "brains do not secrete thought as the liver secrets bile, but that they compute thought as electronic computers calculate numbers" (McCulloch, u.d., ca. 1960s, 12; Lettvin, 1989b and 1989d, 517). It is not simply that computers inspired models of cognition, rather, in a continuous dialectic between the nervous system and the behavioral machine, the mind and the computer became models for each other.

These cortical maps also convinced McCulloch that the pulses moving down preexisting paths from one place to another, inhibiting or exciting, engendered perception, thinking, and memory. If these pulses could be expressed as all-or-none entities, then the language with which the brain talks to itself could consist of strings of zeroes and ones. Such a computing device, proposed in 1937 by Alan Turing – the same year that Claude Shannon completed his MIT thesis on the application of Boolean algebra to relaying and switching circuits – became McCulloch's model for the brain. Leibniz – the patron-saint of cybernetics according to Norbert Wiener provided the philosophical solution: Monads. These indivisible units of perception Leibniz's solution to the dilemmas of Cartesian dualism – became McCulloch's "psychons" and his way of unifying matter and form (McCulloch u.d., ca. 1960s, 13; Leibniz, [1714] 1991; Turing 1937; the Entscheidungsproblem, or "decision problem" was formulated by David Hilbert). Thus several elements in his project date back to earlier decades and centuries but they were reconfigured anew within an emergent representational space formed, in the early 1940s, by the intersection of digital electronic computing, information theory, feedback systems, and military technologies. It is these binary informational monads, or psychons, which became McCulloch's quest for immanence – the cosmic mind – as he embarked on building up a research team that would lay biological foundations for psychiatry at the University of Illinois, then emerging as a major research center for communication and control.

The new psychiatry department included neither behavioral nor psychoanalytic projects (McCulloch considered psychoanalysis a "delusion"). His group engaged in traditional neurophysiology (using monkeys as an experimental model), including wartime contracts

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4 Joannes Gregorius Dusser de Barrenne was the protégé of Rudolph Magnus, (the last student of Hermann von Helmholtz); his article, "The Physiological A Priori," (Dusser de Barrenne 1930) articulates the neoKantian project in physiology. I thank Cornelius Borck for tracing this reference for me. Helmholtz's neo-Kantian interpretation in the natural and life sciences are ubiquitous in his writings and lectures, see Kahl 1971, Introduction and passim. On neo-Kantian German physiology, see Lenoir 1989, esp. Introduction.

for chemical and biological warfare that continued during the Cold War. Thus McCulloch's mathematical quest for the logos was not at the center of his institutional program at Illinois (this changed after his move to MIT a decade later). But his affinity for engineering and military technologies drew him to work on information and control systems at the university and to collaboration with colleagues, such as, Henry Quastler and Heinz von Foerster, at the intersection of biology, information theory, and computing. McCulloch was immersed in shaping a new field that would soon become known as cybernetics, joining forces with Norbert Wiener and John von Neumann (McCulloch 1953; McCulloch u.d., ca. 1960s, 14; see also Kay 1997).[5]

McCulloch knew of Wiener's work in electrical engineering and of his forays into neurophysiology. He then met Wiener around 1941-42 through their mutual friend, the Harvard neurophysiologist Arturo Rosenblueth, who was working with Walter B. Cannon on problems of homeostasis and supersensitivity of denervated structures. With the United States' entry into World War II (1942), Wiener began working with the MIT engineer, Julian Bigelow, on war projects sponsored by the Applied Mathematics Panel (AMP) of the Office of Scientific Research and Development (OSRD). In studying the mathematical aspects of guidance and control of aircraft fire they quickly reached the conclusion that any solution of the self-correcting tracking problem was predicated on the feedback principle, in the plane and the human gun operator. They modeled their analyses after the feedback neuro-mechanisms involved in muscle tremors.

The resulting paper, "Behavior, Purpose and Teleology" (1943), introduced new representations of control systems as conjunctions of physiological homeostasis, engineering servo-mechanisms, and behavioral processes. The cybernetic organism – a heterogeneous construction, part living and part machine – germinated within the wartime academic-military matrix and would mature within the national security practices of the Cold War. The ontology of the enemy, as Peter Galison aptly put it, thus became deeply embedded within a new, military-inspired epistemology. The paper formed a kind of manifesto for cybernetics, first presented in May 1942 at the Cerebral Inhibition meeting in New York, sponsored by the Josiah Macy Jr. Foundation. Thereafter, McCulloch and Rosenblueth conspired with the Foundation's medical director, Frank Fremont-Smith, to sponsor a series of interdisciplinary meetings to spread the gospel of the new science. These famous Macy conferences on cybernetics under McCulloch's chairmanship were launched in 1946; by that time his work with Pitts, despite its technical obscurities, loomed large on the landscape of cybernetics and digital computing (McCulloch, u.d., ca. 1960s, 17-18; Rosenblueth, Wiener, and Bigelow 1943; and for analysis of that work, Kay 1997; on Wiener's war activities, see Heims 1980, ch. 9; Galison 1994, 228-265. On the 1942 conference, see Heims 1991, 14-17; Aspray 1992, 186-187. See also Hayles 1998).

McCulloch first presented his ideas on the binary information flow (on-off) through ranks of neurons in 1941 in Nicholas Rashevsky's seminar on mathematical biology at the University of Chicago. There he met the seventeen-year-old Pitts, a student of Rashevsky and Rudolf Carnap, occupied with the regenerative activity in closed loops (reverberating circuits). While Rafael Lorente de Nó had already shown their significance in vestibular systems,

5 The activities of McCulloch's laboratory are reflected in his correspondence, APS, McCulloch Papers, BM 139 no. l, 1941-1951, including numerous folders on biological and chemical warfare. Information on Heinz von Foerster and Henry Quastler was gathered in my interview with von Foerster, June 26, 1994.

McCulloch sought to extend the scope of their applicability. He thought they could explain phantom limb phenomena (pain persisting after amputation and even after section of the spino-thalamic tract), the early stages of memory conditioning, compulsive behavior, anxiety, and the enduring effects of shock therapy Since there obviously were negative feedbacks within the brain, why not regenerative ones? (McCulloch u.d., ca. 1960s, 14-15; Lorente de Nó 1932 and 1933).[6]

Lone and otherworldly, Pitts possessed a phenomenal intellect and mastery of logic that governed his fragile Platonic soul. This embodiment of pure reason and ego-less mind found refuge in the community of the McCullochs' home. Their partnership enabled McCulloch to formulate his long-standing concepts of nervous nets. For two years – working into the small hours of the night, often leavened by McCulloch's fine bottle of Scotch – McCulloch and Pitts grappled with these problems, harnessing Pitts' phenomenal command of modular mathematics (topology, set and group theory, logic and Boolean algebra). The project's epistemic and methodological foundations rested on the pillars of logical empiricism: Russell and Whitehead, *Principia Mathematic*a and Carnap, *The Logical Syntax of Language*. These were readily translated into operations of Boolean algebra and the two-valued logic of Shannon's information theory.[7]

McCulloch was familiar with Russell and Whitehead's and Carnap's works and their propositional logic since the 1920s. But it was only through collaborating with Pitts that they were able to fully exploit the technical arsenal of the *Principia* and *Logical Syntax* toward a new theory, a logical calculus of immanence: neuronal interactions, or neural nets, expressed as propositional functions that would produce statements constitutive of perception, ideas and/or mind. They wrote in the abstract,

> Because of the "all-or-none" character of nervous activity, neural events and the relations among them can be treated by means of propositional logic. It is found that the behavior of every net can be described in these terms, with the addition of more complicated logical means for nets containing circles; [reverberating/regenerative] and that for any logical expression satisfying certain conditions, one can find a net behaving in the fashion it describes. (McCulloch and Pitts 1943, 115)

This concept was deceptive in its parsimony and elegance. Above a certain threshold voltage, neurons are excited to produce a "yes" signal; below that threshold, or by inhibition, they produce a "no" signal; several neurons (or their axons) could act together on a neuron (spacial summation), or inhibit its firing. Modifications – such as, temporal summation,

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[6] I thank Katharina Schmidt-Brücken for sharing the papers of Lorente de Nó with me. At the time McCulloch was not yet familiar with the path-breaking article by Kubie, "A Theoretical Application to Some Neurological Problems of the Properties of Excitation Waves which Move in Closed Circuits" (Kubie 1930).

[7] Walter Pitts (1923- ca. 1970) as a historical subject, poses significant difficulties for he left no paper trail; in fact, in the late 1950s he destroyed much of his work. He was a teenage runaway from home who found refuge in the McCullochs' home (Jerome Lettvin lived there too and they remained close friends until Pitts' death). Pitts' withdrawn personality prevented anyone from getting to know him, a situation which worsened with time (several psychiatrists participating in the Macy conferences felt that his bizarre behavior was psychotic and there are even intimations that he committed suicide) (see Heims 1991, especially chs. 3 and 6; for biographical information on Pitts, see Lettvin 1989a, 1989c and 1989d. See also Lettvin 1998. On logical empiricism undergirding the McCulloch-Pitts project, see Whitehead and Russell [1910] 1997. See also Richardson 1996a, 1996b; Carnap 1934, 1937; Sarkar 1992.

facilitation, extinction, and learning – were translated into their logical equivalents. Thus the properties of neural nets were amenable to both logic and Boolean algebra; various permutations of nets yielded a given outcome (a signal) and all these equivalent permutations could be described via logical statements generated through propositional functions.

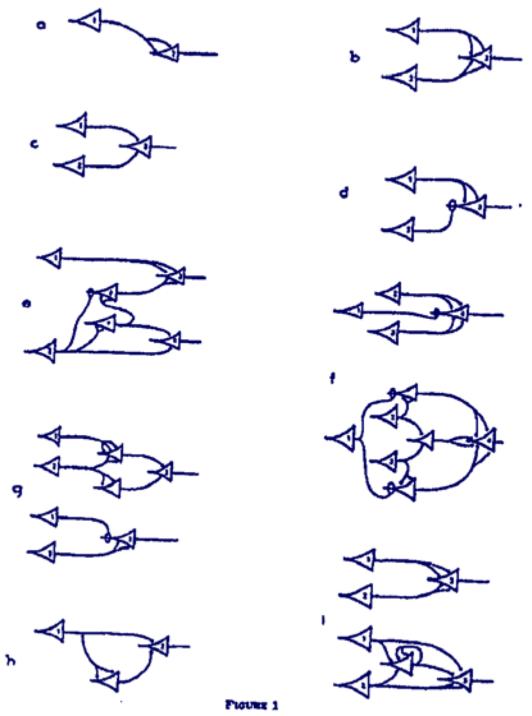
An essential new element in this theory was the introduction of *time*. If neurons were to compose a computer of propositional calculus, then one had to take into account that, if the spikes arriving on the axons of two neurons represent truth values of some two propositions, then the neuron computing the logical operation on these two input propositions can give its answer only a cycle-time later than the time of input production (but tune-variations for different lengths and types of neurons were deliberately neglected). The cycle-time then is the time unit for the operations of neural nets (see fig. 1).[8]

McCulloch was the first to admit that these formal neurons were not realistic, deliberately as impoverished as possible. He pointed out that real neurons can compute not only any Boolean function of their inputs, but also many others. (Moreover, some aspects of neural actions are not digital but analogue; and not only serial but also parallel processes characterize neural interactions). Like frictionless Newtonian surfaces and Bohr atoms, the McCulloch-Pitts neural nets were idealizations, abstract models. And they were a specific kind of models – axiomatized models – where modeling was predicated first on conversion of a phenomenon into a mathematical-logical operation (Dahan 2000). But they were also poetic distillations, reflecting McCulloch's esthetic sensibilities. For like poetry, the McCulloch-Pitts model sought to capture a phenomenological essence through sparseness, abstraction, patterns, and an interplay of rules and liberties. And like poetry, which deliberately deploys enigmatic structures to aim at higher wisdom, neural nets were contrived enigmatically to explicate, from first principles, the fundamental mechanisms for the emergence of perception and mentality

The implications for psychology seemed enormous, promising to elevate it to its full potential as human information processing. It would become a science of signals with clearly defined units of perception – psychons – and precise of rules of formation and transformation for representing mental states (à la Carnap).

> To psychology, however defined, specification of the net would contribute all that could be achieved in that field – even if the analysis were pushed to ultimate psychic units or "psychons," for a psychon can be no less than the activity of a single neuron. Since that activity is inherently propositional, all psychic events have an intentional, or "semiotic," character. The "all-or-none" law of these activities, and the conformity of their relations to those of the logic of propositions, insure that the relations of psychons are those of the two-valued logic of propositions. Thus in psychology, introspective, behavioristic, or physiological, the fundamental relations are those of two-valued logic. (McCulloch and Pitts 1943, 131)

8 In this figure the original notations of the equations have been replaced by modern logic notations. By all accounts (including McCulloch's later reflections) the cumbersome combination of Carnap's and Russell and Whitehead's notations made the paper unnecessarily inaccessible. I thank Tom Stapelford and Joe Dun-lit for their help in accessing the paper and these figures.



Neurophysiological Equivalents
a. Precession
b. Disjunction
c. Conjunction
d. Conjoined negation
e. ?
f. Relative inhibtion
g. (Top) extinction (bottom) absolute inhibition
h. Temporal summation i. Regeneration (learning)

a. $N_2(t) = N_1(t\text{-}1)$ b. $N_3(t) = N_1(t\text{-}1) \vee N_2(t\text{-}1)$
c. $N_3 = N_1(t\text{-}1) \wedge N_2(t\text{-}1)$ d. $N_3(t) = N_1(t\text{-}1) \wedge \sim N_2(t\text{-}1)$
e. $N_3(t) = N_1(t\text{-}1) \vee [N_2(t\text{-}3) \wedge \sim N_2(t\text{-}2)]$
f. (up) $N_4(t) = \sim N_1(t\text{-}1) \wedge [N_2(t\text{-}1) \vee N_3(t\text{-}1)] \vee N_1(t\text{-}1) \wedge N_2(t\text{-}1) \wedge N_3(t\text{-}1)$
f. (down) $N_9(t) = \sim N_1(t\text{-}2) \wedge [N_2(t\text{-}2) \vee N_3(t\text{-}2)] \vee N_1(t\text{-}2) \wedge N_2(t\text{-}2) \wedge N_3(t\text{-}2)$
g. $N_3(t) = N_2(t\text{-}2) \wedge \sim N_1(t\text{-}3)$
h. $N_2(t) = N_1(t\text{-}1) \wedge N_1(t\text{-}2)$
i. $N_3 = N_2\,(t\text{-}1) \vee [N_1(t\text{-}1) \wedge N_1(x)\;\; N_2(x)]$ were "x" is any time before t-1.
N_i is the action of neurons c_i of a given net

Fig. 1. Adapted from Warren S. McCulloch & Walter Pitts 1943. The original notations of the equations have been replaced by modern logic notations.

The perceived benefits for psychiatry were equally grandiose, seeking to place all mental and behavioral phenomena on rigorous neurophysiological foundations.

> Thus both the formal and the final aspects of that activity which we are wont to call mental are rigorously deducible from present neurophysiology. The psychiatrist may take comfort from the obvious conclusion concerning causality -that, for prognosis, history is never necessary. He can take little from the equally valid conclusion that his observables are explicable only in terms of nervous activities which, until recently, have been beyond his ken .... Certainly for the psychiatrist it is more to the point that in such systems [nervous nets] "Mind" no longer "goes more ghostly than a ghost" [Sir Charles Sherrington's expression] Instead, diseased mentality can be understood without loss of scope or rigor, in the scientific terms of neurophysiology (Ibid., 132)

In this way neurophysiology could expand to embrace mind, since that mind conceptualized within a new discourse of information – could now be embodied in neural nets and investigated experimentally.

II. Logical Minds: "Man-Made and Begotten"

Although the 1943 paper of McCulloch and Pitts was a highly idealized mathematical abstraction of a neurophysiological model, its practical potential for automation did not escape their notice. Their conclusion casually pointed to neural nets' equivalence with general Turing machines, "man-made or begotten."

> One more thing to be remarked in conclusion. It is easily shown: first 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; second, that each of the latter numbers can be computed by such a net, and that nets with circles [regenerative] can be computed by such a net. (Turing 1937)

Turing, the first to study the logical possibilities of electronic digital computers in the late 1930s, had been developing them during World War II and the Cold War. Wiener, himself at the forefront of computing, immediately grasped the far-reaching implication of the work of McCulloch and Pitts and conveyed its significance to his friend John von Neumann at Princeton's Institute for Advanced Study (IAS). In fact, in the fall of 1943, Pitts moved to MIT to work with Wiener, where he was exposed to Shannon's information theory, electrical engineering, and to von Neumann's new work in computing. But Pitts was soon snapped up by Kellex Corporation, the Manhattan arm of the atomic bomb project, where he worked for two years before returning to Wiener and neural nets (Aspray 1992, 177-78; Lettvin 1989d, 516).

The construction of computing machines had by then proved essential to the war effort and was proceeding vigorously at several centers in the United States. Harvard, Aberdeen Proving Ground, and the University of Pennsylvania were already constructing such machines. The IAS and MIT were just entering the field, moving from mechanical to electrical relay and assembly, and from the scale of ten to the scale of two. Wiener was spreading the new ideas to all the leading computer scientists: "Everywhere we met with a sympathetic hearing, and the vocabulary of the engineers soon became contaminated with the terms of the neurophysiologist and the psychologist" (Wiener 1945/61, 14-15). As a result of this trans-disciplinary interest, von Neumann and Wiener held a joint conference on control and communication in the winter of 1944; engineers, physiologists; McCulloch and Lorente de Nó, and mathematicians were all represented (see Aspray 1992, ch.8).

The meeting had made it clear that a substantial new field was in the making. Even before the war ended, Wiener and von Neumann, like many of their academic colleagues, began planning for the opportunities in a postwar scientific order. Early in 1945 Wiener announced to Rosenblueth (now back in Mexico; their long distance collaboration supported by the Rockefeller Foundation) plans to organize a society (tentatively named "Teleological Society") and a journal (perhaps to be entitled *Teleologia*), and to found a research center "in our new field" (later named "cybernetics"). The bottleneck was the declassification of relevant war work, but resources appeared to be abundant. According to Wiener,

> In this matter Moe [Henry Allen Moe, head of the Guggenheim Foundation and Rockefeller Trustee] is giving his will and expects to be able to help us with fellowships. We are also getting a good backing from Warren Weaver and he said to me that this is just the sort of thing that Rockefeller should consider pushing. In addition McCulloch and von Neumann are very slick organizers, and

> I have heard from von Neumann mysterious words concerning some [sic: sum of ?] thirty magacucks [megabucks?] which is likely to be available for scientific research. Von Neumann is quite confident that he can siphon some of it off (Wiener to Rosenblueth, January 24, 1945. MIT Archives, Wiener Papers, MC 22, Box 2.67)

Von Neumann agreed that "we ought to interest anybody and everybody and then see what happens .... The best way to get something done is to propagandize everybody who is a reasonable potential support" (von Neumann to Wiener, April 21, 1945. MIT Archives, Wiener Papers, MC 22, Box 2.68;. see also Kay 1997). Their vision materialized in the Macy conferences on "Feedback mechanisms" and "Circular Causal Systems in Biology and the Social Sciences." Under McCulloch's leadership, the Conferences on Cybernetics, as they came to be called, provided an interdisciplinary forum and a kind of "seed" money for subsequent military-industrial investments.

As with McCulloch, von Neumann's work was driven by two passions: mathematics and the military; his academic collaborations and extensive military consulting projects (such as electronic computing and even game theory) were often intertwined. Von Neumann had been interested in the relation between Turing's machine and the brain since the late 1930s (in 1938 he offered Turing an assistant's position at the IAS). These ideas of axiomatizing cerebral action were influenced through a correspondence (1939-1941) with his Hungarian mentor Rudolf Ortway But their elaboration was shaped by new representations of communications, which have crystallized around information theory and cybernetics, including McCulloch-Pitts neural nets; their model fit perfectly with von Neumann's embryonic theories of automata. To be sure, von Neumann was critical of some of the assumptions behind those primitive neurons (deliberate simplifications, which were clearly outlined in their 1943 paper). Nevertheless, their nets, especially closed loops, or reverberating circuits, became the model for his design of the memory of the EDVAC.

> While it appeared, that various parts of this memory have to perform functions which differ somewhat in their nature and considerably in their purpose, it is nevertheless tempting to treat the entire memory as one organ, and to have its parts even as interchangeable as possible for the various functions enumerated above .... The three specific parts CA [central arithmetical], CC [central control] (together C) and M [memory] correspond to the *associative* neurons in the human nervous system. It remains to discuss the equivalents of the sensory or *afferent* and the *motor* or *efferent* neurons. These are the input and output organs of the device, and we shall now consider them briefly. (von Neumann [1943] 1973, 357)

McCulloch-Pitts neural nets and Turing's machine became the twin pillars of early automata studies and computer design (on von Neumann and Ortvay, see Aspray 1992, 178-80. See also von Neumann 1958; and Schmidt-Brücken 1998). And just as with Wiener's cybernetics, in which the nervous system became a model for negative feedback machines and, in turn, the machine as a model for biological systems, this cyborg dialectic obtained also in logical automata. Neural nets became a model for the electronic memory and, in turn, the computer would become a model of cognition.

Thus from a historical vantage point, the work of McCulloch and Pitts, remarkably original as it was, can be seen as a culturally situated epistemology. It burst into the technoscientific scene at a moment when seemingly independent strands – cybernetics, information theory, and electronic computers – were coalescing into a new area of communication and control with discernable intellectual coherence.

Shaped by the mandate of World War II, the new field carried enormous social consequences for the postwar era. Due to its potential for industrial automation and strategic defense power; both von Neumann and McCulloch worked closely with the military The Yale philosopher F. S. C. Northrop (McCulloch's mentor and friend, and a participant in the Macy conferences) expressed his concerns to Wiener in 1947.

> All this ideological business [the social implications of cybernetics] is nothing but window-dressing and a rationalization after the event for rough-and-tumble scrapping in the power politics field. What this amounts to, if one acquiesces in it, is the continuation of a situation in which the power politics boys, the militarists, instead of the scientifically informed people, give the machine its major teleological instructions. (Northrop to Wiener, May 5, 1947. APS, McCulloch Papers BM 139, no.1)

By the early 1960s the military establishment would come to honor McCulloch as "the High Priest of Cybernetics, Bionics, or Self-Organizing Systems, whatever you call it" (Lt. Col. Callahan, Jr., to Lt. Col. Sieber, Jr., December 12, 1962. APS, McCulloch Papers BM 139, no.1).[9] Indeed, in the postwar decade McCulloch was operating on three fronts, all with some links to the military. He was building up cybernetics by serving continuously as the chairman of the Macy conferences (1946-1953), several of them linked to CIA (Central Intelligence Agency) interests. He continued to guide the research in neurophysiology, including biological warfare projects, in his Illinois laboratory until his move to MIT in 1951. And he developed the neural nets project; his cybernetic network extended beyond the United States, notably to the Ratio Club in England (Albert Uttley, Grey Walter, Ross Ashby, Donald MacKay, Dennis Gabor, Colin Cherry). With a growing international young following from medicine and engineering, and rising military interest, McCulloch's project at MIT during the years 1951 to 1969 became coextensive with studies of automata artificial intelligence (AI).[10]

McCulloch was not an AI enthusiast. He was far less interested in machines that try to think than in the mechanical principle of thought (and by mechanical he did not mean physico-chemical or reductionist). He was attracted to "Machines that Think and Want": how we know particulars and universals, the desire for food, woman and bed, music, poetry, mathematics. And he sought a mathematical corrective to the mindless blackbox of behaviorism and the tripartite Platonic conjectures of psychoanalysis. Yet, according to his protégé, Jerome Lettvin and the AI pioneers (e.g. Mallory Selfridge, Seymour Papert, Marvin Minsky, and Michael Arbib), McCulloch's work is considered to be the foundation of AI.

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9 The McCulloch Papers contain numerous folders of his work with the Air Force, Army and Navy (including a certificate of honor). He was a militant anti-communist and was deeply committed to the Cold War.

10 McCulloch was especially impressed with the work of the late Kenneth Craik. Craik 1943 and Craik 1966 were published posthumously with McCulloch's support (see e.g. Craik 1947-48; Zanwill 1980; Bartlett 1946). I am grateful to Cornelius Borck for providing me with these materials. On the British cybernetic scene, see Ashby 1952; Walter 1953, and Cherry 1957. See also Pickering 2000 and Hayward 2001, in this volume. McCulloch's move to MIT in 1951 was motivated largely by the plans of close work with Wiener, but within a few years a major falling out between Wiener and McCulloch thwarted any collaboration. This was a source of disappointment to McCulloch and his group (especially Pitts) and they never quite recovered from that trauma.

For example, one of the early studies, following in the heels of the "Logical Calculus," was McCulloch's theoretical analysis, "The Heterarchy of Values Determined by the Topology of Nervous Nets" (1945): a preliminary introduction to nets describing purposive activities, namely, circular, non-hierarchical nets, that he christened "heterarchy" He demonstrated that in such nets, when stimuli appropriate to a number of actions are present, then only the most valued action will be emitted. In order to demonstrate that the architecture of such a neural net in no way implied a strict hierarchical ordering of actions, he constructed a net which, confronted with three choices: A or B, B or C, and C or A, emit A rather than B, B rather than C, but C rather than A. This concept of heterarchy and its terminology became incorporated in the literature of Artificial Intelligence.[[11]]

A subsequent and key contribution to AI was the classic study by Pitts and McCulloch, "How We Know Universals" from 1947. Viewing the brain as the center for information processing and the nets as its organizing apparatus they sought means of recognizing an object despite drastic changes in apparition (appearance).

> Numerous nets, embodied in special nervous structures, serve to classify information according to useful common characters. In vision they detect the equivalence of apparitions related by similarity and congruence, like those of a single physical thing seen from various places. In audition, they recognize timbre and chord, regardless of pitch. The equivalent apparitions in all cases share a common figure and define a group of transformations that take the equivalents into one another but preserve the figure invariant .... We seek general methods for designing nervous nets which recognize figures in such a way as to produce the same output for every input belonging to the figure. We endeavor particularly to find those which fit the histology and physiology of the actual structure. (Pitts and McCulloch 1947, 127-28)[[12]]

This study was an exemplar of "experimental epistemology."

Grounded in the histology, anatomy, and physiology of specific structures, McCulloch and Pitts analyzed mathematically how, in "scanning," pattern recognition could be preserved despite changes in size, rotational displacement, or position of an object; and how a pattern could be brought to "standard form" when the gaze is shifted. They demonstrated that information-coding in the brain is a topographically-organized activity distributed over layers of neurons and that computations could be carried out in a distributed fashion by a

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[11] On the relation between McCulloch's work and the beginning of AI, see, for example, McCulloch 1945 and 1950; Lettvin 1989a; Selfridge 1989; Arbib 1989a. Some of the AI works which build directly on McCulloch's are Shannon and McCarthy 1956; Rosenblatt 1962; Minsky 1967; Minsky and Papert 1969; Arbib 1972 and 1988.

[12] As Michael Arbib has pointed out, their paper was written before microclectrodes revolutionized neurophysiology by enabling experimenters to monitor the activity of single neurons. But it spurred Lettvin and his MIT collaborators toward a study of vision and pattern recognition that would become a classic in single-cell neurophysiology and cognitive neuroscience (Arbib 1989b, 511). Lettvin et al. 1959 analyzed the activity of single fibers in the optic nerve of a frog and showed that it was not the light intensity but rather the pattern of local variation of intensity that is the exciting factor. They identified four distinct, parallel, distributed channels whereby the frog's eye informs his brain about the visual image in terms of local pattern. And though that work, as they pointed out, applied only to the frog (the human visual system is anatomically and physiologically different), McCulloch felt that it was a major step toward an experimental epistemology.

collection of neurons without the intervention of a *sensorium commune*. As earlier, these studies were intended only as plausible models.

> If mistaken, they still present the possible kinds of hypothetical mechanisms and the general character of circuits which recognize universals, and give practical methods for their design .... Our circuits extend the abstraction to a wide realm of properties. (Ibid., 146)

And so it did. It offered new perspectives in neurophysiology, new goals for research in single-cell neurophysiology, and for studying mechanisms of human and artificial vision. It too was an important contribution to problems of pattern-recognition, to AI, for the design of scanning and imaging devices (with a wide range of military applications), and to the emergent trend of cognitivism.[13]

That collective move toward cognitivism (and a deliberate challenge to behaviorism) was spearheaded in 1948 with the Hixon Symposium, "Cerebral Mechanisms in Behavior," at the California Institute of Technology. Its mandate was to begin to explore various embodiments of mind and behavior. Von Neumann and McCulloch initiated the presentations of the illustrious gathering, which included neurophysiologists, psychiatrists, and psychologists. Indeed the two papers, "The General and Logical Theory of Automata," and "Why the Mind is in the Head," complemented each other, highlighting the scopes and limits of their respective projects, their convergences and divergences. Von Neumann readily conceded that, at that point in time, living organisms and automata (computing machines) were not fully comparable.

> The living organism is very complex – part digital and part analogy mechanisms. The computing machines, at least in their recent forms .... are purely digital. Thus I must ask you to accept this oversimplification of the system. I shall consider the living organisms as if they were purely digital automata. (von Neumann 1951, 10)

Yet this digital oversimplification granted, he estimated that the possibilities for automata opened up by the McCulloch-Pitts model were enormous.

> It has been attempted to show that such specific functions [the human nervous system], logically, completely described, are per se unable of mechanical neural realization. The McCulloch-Pitts result puts an end to this. It proves that anything that can be exhaustively and unambiguously put into words, is ipso facto realizable by suitable finite neural networks. (Ibid., 22-23)[14]

McCulloch too pondered the scope and limits of automata. He acknowledged that, through improvement, they were destined to assume prominence in the postindustrial era (with a

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13 On the relation of automata studies and the Cold War, see Edwards 1996.

14 It took three years to publish the proceedings, in part due to von Neumann's delay in writing up his notes. On the significance of the Hixon Symposium for cognitive science, see Gardner 1985, chap.2. For general trends in psychology in the twentieth century see Smith 1997, part V; von Neumann 1951, 10, 22-23; McCulloch 1951. Von Neumann's specific objections to the McCulloch-Pitts model was communicated to his friend Karl Friedrich Bonhoeffer (cousin of Max Delbrück), biophysicist and director of the Max-Planck Institute for physical chemistry in Göttingen (von Neumann to Bonhoeffer, April 1, 1949. Von Neumann Papers, Box 2.11. Washington, Library of Congress. See also, von Neumann 1958. On von Neumann's automata theory, see Aspray 1992, chap.8; and Kay 1997.

threat of technological unemployment); and they would also force us to rethink the relations between machines and humans; what makes us human.

> As the industrial revolution concludes in bigger and better bombs, an intellectual revolution opens with bigger and better robots .... These machines, whose evolution competition will compel us to foster, raise the appropriate practical question: "Why the mind is in the head?" Coming as I do between psyche anatomized and psyche synthesized, I must so define my terms that I can bridge the traditional gulf between mind and body and the technical gap between things begotten and things made. By the term "mind," I mean ideas and purposes. By the term "body," I mean stuff and process .... It is these regularities, or invariants [in the flux of events], which I call ideas .... Ideas are then to be construed as information .... Our knowledge of the world, our conversation – yes, even our inventive thought – are then limited by the law that information may not increase on going through brains, or computing machines. (McCulloch 1951, 42)

Given these definitions and constraints, there were unbridgeable differences – ontological and practical – between humans and automata; even in the idealized digital model of McCulloch and Pitts.

Computers could not carry out computations, no matter how simple, in hundred parallel paths and demand coincidence, McCulloch argued. Thus no computing machines were likely to function properly under conditions as diverse as human experience. Moreover, neurons are cheap and plentiful, he noted. Von Neumann would be happy to have their like for the same cost in his robots. McCulloch calculated that it might take only 10 million tubes; but it would take Niagara Falls to supply the current and the Niagara River to carry away the heat. And one would also have to specify all the information in advance. This could not be a genetic program.

> As we have 10^{10} neurons, we can inherit only the general scheme of the structure of our brains. The rest must be left to chance. Chance includes experience which engenders learning. Ramón y Cajal suggested that learning was the growing of new connections .... This brings us back to what I believe is the answer to the question: Why the mind is in the head? Because there, and only there, are hosts of possible connections to be performed as time and circumstance demand. (Ibid., 54-55)

Despite his penchant for engineering, McCulloch reasoned not from an AI perspective but from a psychiatric one. Neural nets, he argued at the Anglo-American Symposium on Psychosurgery in 1948, held the answer to key problems of the backward disciplines of psychology and psychiatry: memory, conditioning, compulsive behavior, and other neuroses. In his paper, "Physiological Processes Underlying Psychoneuroses," he even worked out in detail a concrete case study: the neural nets underlying causalgia (a burning sensation), representing it as a servomechanism gone astray through reiteration, a perversion of a reflexive circuit "gremlins" as engineers called them. The mechanisms of causalgia were instructive, he believed, for they could serve as a physiological model for general mechanisms of neurosis, the gremlins, or demons, inside the body's servomechanism.

> These properties together describe more exactly what Lawrence Kubie has called the "repetitive core" of every psychoneurosis. The difference is that the latter begins elsewhere, in appetitive circuits [instead of the reflexive circuit]. (McCulloch 1949/1989, 611)

In fact, McCulloch argued, the causalgie mechanism also shed light on the unconscious, or on distinction between conscious processes and those which have been shut out of consciousness to generate neuroses. It could also explain, in physiological terms, the manifestation of repression and resistance. Indeed, this case-study was to be a lesson for psychologists and psychiatrists, arrested in what McCulloch considered to be a medieval frame of mind. He felt that the medieval schism between revelation and reason characterizing the age of Thomas Aquinas was now mirrored in the schism between psychology and physiology in the understanding of diseases called "mental"; Freud's trichotomy of the soul was merely an extension of Plato's political psychology.

> His [Freud's] epigoni, the latterday illuminati, those new perfectibillians, have dethroned reason but to install social agencies, analytical interviews and transferences in the places of espionage, confession and conversion, and fail to add a cubit to our stature. (Ibid., 607)[[15]]

For McCulloch, the psychiatrist, experimental epistemologist, poet, militarist, and theological engineer, the real bridge between soma and psyche was the art of communication as the science of signals. Signal-bearing neural nets were the model of command and control in all machines, "man-made and begotten." This cybernetic ascendance from logical neurons to embodiments of mind was to be the key to normal and aberrant behavior, to the workings of the psyche, and to the logical and poetic essence of humanness. Bridging Matter and Form, neural nets were to bring us closer to the monadic mind of God through the equation of mind with logic. For "it is but a reincarnation of Saint Thomas' faith that God did not give us our senses to fool us," McCulloch insisted (McCulloch 1948/1989, 894). In abandoning the futile *Mysterium Iniquietatis of Sinful Man Aspiring into the Place of God*, Man could finally come within reach of the transcendental logos (McCulloch 1955).

McCulloch convinced neither psychologists nor psychiatrists (though he was an active member of American Psychiatric Association); the neurophysiologists, preoccupied with amassing empirical knowledge, were generally suspicious of theories of mind. His neuropoetic distillations were regarded as out of touch with physiological realities. Instead, the McCulloch-Pitts model attracted mavericks willing to cross boundaries among mathematics, electrical engineering, physiology, psychiatry, and psychology. Neural nets thus became central to the emergent fields of cybernetics, computer science, artificial intelligence, automata studies, robotics, and self-organizing systems, areas that offered novel approaches to studies of perception, memory, and learning, mind-body, the natural and the artificial. And beyond reified theories and exotic laboratory gadgets, these researches became central for

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15 At that time he had already become familiar with Kubie's 1930 work but by then Kubie had abandoned this physical and quantitative approach to psychiatry (see Kubie 1947). Although Kubie was a frequent participant in the Macy conferences by 1953 they had a major falling out (especially after McCulloch's attack on psychoanalysis in lecture, "Past of a Delusion"), APS, McCulloch Papers, BM 139, Lawrence S. Kubie (folders I and II). McCulloch had an exceptionally hostile relation to psychoanalysis. He felt that eccentricities and deviations from "norms" are central to self-expression and creativity (for example, himself and Pitts). His extreme individualism and unconventional life-style (for example, he had an "open-marriage" and "open house") did not lend itself to being judged by psychoanalysts. See also, Heims 1991, chap.6.

the design of command and control technologies and a prime military investment in the postwar era.[16]

> When I am dead let no man say
> That, had I lived, I had done so and so:
> For I was always on an unknown way
> To mine own ends, the which they could not know!
>
> No more could I, who ended every day
> Surprised by the success of my strong go
> Toward when I did not dream
> I would essay
> Or, having won, would hold it was enough
>
> We're moved by springs that carry their surcease
> That we unwittingly mistake for goals –
> They are but ends unknown before they're had
>
> Yet, once its clear they can no more increase,
> We quit that tack, like ships that near the shoals
> A course, which to pursue, were surely mad!
>
> Warren S. McCulloch (McCulloch 1989, vol. 3, 955).

Conclusion

How do we assess the McCulloch-Pitts neural nets project? Did it offer enduring contributions to cognitive science? Or were these poetic distillations just castles in the air? The work of McCulloch and Pitts is surely regarded as the foundation of brain modeling, computational neuroscience, and Al. According to James A. Anderson, a leader in neural nets research, modern brain modeling has had two main approaches, one based on serial processing by digital neurons of extreme specificity, the other based on parallel processing by analog neurons active in numerous patterns; both approaches stemmed from the models of McCulloch and Pitts (Melnechuk 1979, 6-8; Anderson 1983; Amit 1997, chaps.l and 3).[17] However, assessing the contribution of neural nets research in neuroscience is a more complicated task, which is beyond the scope of this article. Neural nets research has attracted considerable funding and prestigious scientific figures, but it is deemed by many neuroscientists as castles in the air that are tumbling down, irrelevant at best and misguided at worst as a means for understanding the human mind.

From an historical vantage point, however, the significance of neural nets (and connectionism, as studies of pattern association) inheres in introducing new, meta-levels analyses to neuroscience. The McCulloch-Pitts approach moved the scientific gaze far beyond the various anatomical localizations and units of study of traditional neurophysiology (sometimes termed the "wet" approach): beyond biochemical and biophysical analyses of mem-

16 Aside from the collaborations with the Air Force, Navy, and Army documented in the McCulloch Papers, see also Hecht-Nielsen 1998, 302-303 on the patterns of funding for neural nets by DARPA (Defense Advanced Research Projects Agency).

17 Many of the contributors to Anderson and Rosenfeld's Talking Nets refer to McCulloch's implicit and explicit role in their careers. Both Varela and Antonio Damasio refer to McCulloch as a visionary and a prophet.

branes, studies of single neurons and other neural cells, dissections of tissues and organs, and even beyond the anatomy and physiology of the central and peripheral nervous system. Indeed, McCulloch's expertise in several of these areas has remained undisputed (recall that he headed a productive traditional neurophysiology laboratory until 1951). Instead, neural nets offered a modeling approach based on experimental data (sometimes called a "dry" approach) which bypassed anatomical localization, viewing the mind as an emergent process out of the interactions (binary operations) of neurons spanning the central and peripheral nervous system. It was a mechanical, but non-reductionist approach to cognition, for the very notion of "mechanical" has been reconfigured in the postindustrial era. As we have seen in Wiener's study of cybernetic systems, von Neumann logical automata and electronic computers, and McCulloch's computational binary neurons, the new machines of the information age – the cyborgs – represented the continuous dialectic between natural and artificial systems, each forming a model and a referent for the other.

Most importantly, the primacy of McCulloch's and Pitts' contributions to cognitivism is indisputable. Cognitivism's formative period, 1943-1953, is coextensive with the rise of cybernetics, information, and computer sciences; in its broad sense, the term "cognitive" science signifies the study of mind. In contradistinction to brain, behavior, or personality, the mind became a legitimate and worthy object of quantitative experimental research, a move initiated with the McCulloch-Pitts 1943 paper. Their program of "experimental epistemology," McCulloch believed, provided an entry to the hard-wiring of the perceptual manifold – to the embodiment of Kant's synthetic *a priori* – and thus access to Man's (and therefore God's) logos. That logos was mathematics and logic. As McCulloch himself stated, the pursuit of the logos was equivalent to the inquiry, "What Is a Number, that a Man May Know It, and a Man, that He May Know a Number," his life-long quest.

But, as we have seen, it was not "the mind" as an eternal and immutable object which McCulloch and Pitts brought into experimental quantitative research in the 1940s. Granted, some diachronic representations – certain eternal images and icons of the soul, anima, and psyche – contributed to the new reconceptualizations of mind, as did earlier philosophical doctrines and mathematical tools (as is always the case in epistemic ruptures). But the particular configurations of these tools and images bore the unmistakable marks of a new, postindustrial episteme: an emergent military technoculture of communication, control, and simulations. Within its regimes of signification, life and society were recast as relays of signals and as information systems. Thus from this historical vantage point the McCulloch-Pitts model of mind as neural nets stands out not only for its cognitive turn and remarkable originality but for exemplifying the new episteme of the information age. And as such, it is instructive as a culturally-situated epistemology, illuminating the historical conditions for representing as sublime an object as the human mind.

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