Title
The Cybernetic Origins of Life

Author
Powers, Kathleen Alicia

Publication Date
2020

Peer reviewed|Thesis/dissertation

The Cybernetic Origins of Life

By

Kathleen A. Powers

A dissertation submitted in partial satisfaction of the requirements for the degree of

Doctor of Philosophy

in

Rhetoric

and the Designated Emphasis in

Science and Technology Studies

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Chair Professor David Bates
Professor James Porter
Professor Emeritus Gaetan Micco
Professor Sandra Eder

Fall 2020

Abstract

The Cybernetic Origins of Life

by

Kathleen A. Powers

Doctor of Philosophy in Rhetoric

and the Designated Emphasis in Science and Technology Studies

University of California, Berkeley

Professor David Bates, Chair

This dissertation elucidates the cybernetic response to the life question of post-World War II biology through an analysis of the writings and experiments of Warren S. McCulloch. The work of McCulloch, who was both a clinician and neurophysiologist, gave rise to what this dissertation refers to as a biological, medical cybernetics, influenced by vitalist conceptions of the organism as well as technical conceptions of the organ, the brain. This dissertation argues that the question 'what is biological life?' served as an organizing principle for the electrical, digital model of the brain submitted in "Of Digital Computers Called Brains" (1949) and the formal, mathematical model of the brain required by the McCulloch-Pitts neuron in "A Logical Calculus of the Ideas Immanent in Nervous Activity" (1943). I argue that, in discussions in these papers of how the brain responds to stimuli, there is a concept of biological life as perceptual life, rendering the brain a biological object with technical attributes whose activity is the activity of world-building. This dissertation analyzes experiments McCulloch performed on living animals to understand how the cybernetic brain was pharmacological and not merely digital or automatic. Finally, this dissertation analyzes writings on the discipline of biology published late in McCulloch's life, which concern the information carrying capacity of water molecules, the reproductive protein called the "Biological Computer," and a thought experiment on building a simulation of man. I claim that McCulloch's "Biological Computer" includes a model of heredity counter to that of DNA, where form and not the program bears life forward.

Table of Contents

Acknowledgements

To my teachers, who have opened up the world: Alicia Brown Powers and James Fitzsimmons Powers II, Jacqueline Fishman, Richard Harris, Karen Glenn, James Scott, Jeffrey Alexander, John Thompson, Francesco Casetti, David Bates, James Porter, Sandra Eder, and Gaetan Micco.

Introduction

I. Theoretical neurophysiology and the question of life

The legacy of Warren S. McCulloch's work in theoretical neurophysiology was the formal representation of the transmission of a neural impulse.[1] McCulloch was a physician conducting experiments on the central nervous system between the years 1934and 1964.[2] He is most famous for the model of the neuron termed the McCulloch-Pitts neuron, which was described in the influential article, co-written with Walter Pitts, entitled "A Logical Calculus of the Ideas Immanent in Nervous Activity" (1943). McCulloch is also well known for the thought experiment comparing the brain to a digital machine, in "Of Digital Computers Called Brains" (1949), co-written with John Pfeiffer.[3] McCulloch was a central figure in the early development of cybernetics, serving as moderator at the early series of meetings, "Circular Causal and Feedback Mechanisms in Biological and Social Systems" (1946-1949)[4] and as chairman of the Macy Conferences on Cybernetics (1949-1953).

Given the importance of McCulloch's work in the history of cybernetics, computing, and computational perspectives on the mind and brain, the question I ask in this dissertation is whether McCulloch's writings on neurophysiology include a concept of *biological life*. I argue that in McCulloch's work, the key technological concepts of feedback chains in control of complex systems, information as negative entropy, and the binary messages of digital signals – concepts that characterize the intervention of cybernetics in the biological sciences – in fact describe a living organism that builds and responds to a world. I will show that McCulloch's training as a practicing neurologist requires close attention to clinical concepts such as therapy, pharmacology and cure, understood from the perspective of a biological and medical cybernetics. The argument is that the body, as the site of both analysis and intervention in McCulloch's research and practice, extends and deepens the biological significance of his cybernetic work. In the period of McCulloch's career, prior to and during the genetic revolution, questions of the mechanism underlying life had not supplanted questions of the organism's ability to self-

---

[1] The work of theoretical neurophysiology is the generation of mathematical, propositional models for how a set of neurons might function. "Theoretical neurophysiology rests on certain cardinal assumptions," Warren McCulloch and Walter Pitts, "A Logical Calculus of the Ideas Immanent in Nervous Activity," in McCulloch *Collected Works of Warren S. McCulloch*, ed. Rook McCulloch, 4 vols. (Salinas CA: Intersystems Publications, 1989), 1: 343.

[2] 1934 is the start of McCulloch's research career as a laboratory scientist at Yale University in the Laboratory of Neurophysiology of Professor Dusser de Barenne at Yale University. Rook McCulloch, "Foreword," *Collected Works* 1:2. One of the final peer-reviewed scientific publications went to press in 1964: "Studies in Carbohydrate metabolism and its regulation in health and disease of the central nervous system," *Annals of the New York Academy of Sciences* (1964): 117(1): 415–424.

[3] "As a device for handling signals, the brain can be conceived as an ensemble of nerve cells or neurons, which act quasi-independently….. Thus, today one speaks of any device for communication which performs its computations by these discrete signals indifferently as either a digital or a logical machine. And all large modern computing machines are principally digital." Warren S. McCulloch and John Pfeiffer, "Of Digital Computers Called Brains,".*The Scientific Monthly* (1949) 69(6): 369.

[4] Claus Pias, "The Age of Cybernetics," in Pias, ed., *Cybernetics: The Macy Conferences 1946-1953* (Zurich and Berlin: Diaphanes, 2016), 12.

regulate, the faculty considered unique to life according to the tenets of 20th-century variations on vitalism. As we will see, mechanistic thinking and a particular kind of vitalism are integrated in McCulloch's writing — an integration required by the many adjustments of scale in his assessments of nervous activity, ranging in dimension from a molecule of water to the vast cortical storage networks of human memory. I argue that McCulloch's writing and research present a challenge to traditional notions of empirical inquiry as well as the theoretical foundations of cybernetic approaches to adaptive "machines," because McCulloch's constant adjustments of scale contextualize and destabilize the central question of "life" as McCulloch understood it. This dissertation argues that life could, on the one hand, be accounted for microscopically as "one class of chemical reactions,"[5] while understood as a specific relation to *world-making*, where the nervous system is positioned as the physiological structure that facilitates the living body's ability to originate a phenomenal world.

The major trends of mid-century theoretical neurophysiology, influenced by notions of homeostasis (Cannon 1929, Bernard 1878), negative feedback (Rosenbleuth, Wiener and Bigelow 1943, Wiener 1948), the universality of discrete-state machines (Turing 1950) and mathematical logic (Whitehead and Russell, 1910), generated mathematical and propositional models of the neuron's signal sending activity. On the preconditions that "the activity of the neuron is an 'all-or-none' process"[6] and that "the nervous system is a net of neurons, each having a soma and an axon,"[7] McCulloch (along with mathematician Walter Pitts) submitted a mathematical representation of the relationship of cells in the nervous system, what they called the Logical Calculus. In the conclusion of the paper, McCulloch and Pitts describe the Calculus as a "law of necessary connection"[8] with which "one can compute from the description of any state that of the succeeding state."[9] Similarly, on the assumption that the output of the neuron can be quantized and rendered in a binary form, McCulloch (with mathematician John Pfeiffer) submitted the first *medical* comparison of the brain and a digital computing machine. The challenge to empiricism inheres in McCulloch's method, where theoretical concepts and the body as a living being *precede* the experimentation and observation that constitute evidence in contemporary neuroscience. Today, we are familiar with transposing images (theoretical and technological) of the brain onto the material surround through metaphor and analogy, and this is, I argue, an articulation of what neuroscience *has always* been and remains so currently – that is, a confrontation with both the impossibility of "seeing" our brain in the world and the impossibility of claiming our brain as our own just through knowledge of its activity. If, as

---

[5] Warren S. McCulloch, Warren S. "Biological Computers" (1957-1958) *The Warren S. McCulloch Papers* at the American Philosophical Society Library. Philadelphia, PA., Box 59, Mss.B.M139.

[6] McCulloch and Pitts, "A Logical Calculus," 346.

[7] Ibid., 343

[8] Ibid., 357

[9] Ibid., 357

scholars such as Fernando Vidal[10] and Catherine Malabou[11] claim, the discipline of neuroscience has changed how the self is conceptualized and has presented the brain as the totality of the self, then "the material and technical orientation of modern neuroscience has in effect alienated us from our own brains."[12] A consideration of McCulloch's work that acknowledges the technical and biological, the neurophysiological and the cybernetic, the medical and the philosophical, can elucidate a concept of life that includes the changes the organism makes in response to the world and the system by which it orchestrates those changes.

II. Towards a medical cybernetics

McCulloch's cybernetics was always a biological *and* medical cybernetics, with clinical correlates either adumbrated in his papers or referred to directly as the inspiration for his work — for example, it was Parkinson's disease witnessed on rounds at Bellevue hospital as a Neurology resident that caused McCulloch to reflect on the possibility of closed loops within the central nervous system: "we wondered whether there was not in them (Parkinson's patients)…a vicious circle in the brain."[13] The body was before and after his work. Its changing states, its pathologies being the cause of scientific inquiry and therapeutic intervention.

Because of the hierarchy perceived in the structure of feedback – the perception that only one component has executive power to change the state of other, constitutive components – and the immutability perceived in the structure of feedback, the perception that a system is unchangeable apart from its deviation from a set point, cybernetics has been described as devoid of the conceptual tools necessary for understanding the dynamism attributed to biological life. Cybernetics has been counterposed with plasticity (Malabou 2008) and with vitalism (Hayles 1999). In *Cybernetics, or Control and Communication in the Animal and the Machine* (1948) Norbert Weiner describes the choice of the term "cybernetics" to name the emergent field:

> We have decided to call the entire field of control and communication theory…by the name *Cybernetics*, which we form from the Greek χυβερνήτης, or *steersman*. In choosing this term, we wish to recognize that the first signifiant paper on feedback mechanisms is an article on governors published by Clerk Maxwell in 1868, and that *governor* is derived from a Latin corruption of χυβερνήτης. We also wish to refer to the fact that the steering engines of a ship are indeed one of the earliest and best-developed forms of feedback mechanisms.[14]

---

[10] FernandoVidal, *Being Brains: Making the Cerebral Subject* (New York: Fordham University Press, 2017).

[11] Catherine Malabou,.*What Should We Do with Our Brain?* trans. Sebastian Rand (New York: Fordham University Press, 2008.)

[12] David Bates, personal communication.

[13] 31. McCulloch, "Recollections of the Many Sources of Cybernetics," *Collected Works,* 31

[14] Norbert Wiener, *Cybernetics, or Control and Communication in the Animal and the Machine* (1948) (Cambridge, Mass.: MIT Press, 1962), 11-2.

James Clerk Maxwell's steam engine, with its "governor" apparatus, was a mechanical feedback system, and it was an inspiration for Wiener's understanding of the key concept in the field of cybernetics, namely the notion of negative feedback, where "the information fed back to the control center tends to oppose the departure of the controlled from the controlling quantity, but it may depend in widely different ways upon this departure."[15] Weiner's chapter "Feedback and Oscillation" notably begins with a discussion of *pathology*: a comparison of *ataxia* in two patients, one of whom is unable to walk due to damages to the spinal cord, and the other who is unable to walk due to damages to the cerebellum, what is assumed to be the nervous system's control center, "proportioning the muscular response to the proprioceptive input."[16] McCulloch and Pfeiffer's "Of Digital Computers Called Brains" (1949) demonstrates a similar understanding of the field of cybernetics: cybernetics is discussed as one branch of the science of signals, oriented towards the negative feedback mechanisms responsible for the large scale, goal-oriented activity of the organism: "it is the program of the branch of the science of signals called cybernetics to analyze all purposive behavior in terms of inverse feedback."[17] Weiner and McCulloch's shared emphasis on negative feedback in biological systems facilitated an interest in modeling how such systems worked. In fact, as Ronald Kline describes in *The Cybernetics Moment*, cybernetics was in effect split into two fields, with McCulloch and Weiner's work belonging to one subfield, the "system's modeling discipline,"[18] and Gregory Bateson and Heinz von Foerster's work belonging to the discipline of "radical epistemology,"[19] which explored the consequences of cybernetics on the processes and nature of human knowing. Kline shows how cybernetics developed alongside information theory,[20] and establishes a relationship between the human-machine analogy and negative feedback[21] during the period of what he terms the cybernetics moment,[22] a period in which cybernetics and information evolved separately after World War II before being subsumed – adopted and modified – in "a utopian information narrative that thrived when the cybernetics moment ended." This information narrative is

---

[15] Ibid., 97.

[16] Ibid., 96.

[17] McCulloch and Pfeiffer. "Of Digital Computers Called Brains," 373.

[18] Ronald Kline, *The Cybernetics Moment, or Why We Call Our Age the Information Age* (Baltimore: John Hopkins University Press, 2015), 5.

[19] Ibid.

[20] "I maintain that the invention of cybernetics and information theory is as important as the invention of information technologies in understanding the present age. At the heard fo the book is what I call "the cybernetics moment" — the rise, fall and reinvention of cybernetics that occurred alongside the rise of information theory in the United States." Kline, *Cybernetics Moment,* 6.

[21] "If the analogy between humans and machines was the founding metaphor of the Macy conferences, the idea of circular causality was the mechanism behind the metaphor." Ibid., 55.

[22] "The cybernetics moment began when the two fields (cybernetics and information theory) emerged shortly after World War II, reached its peak with their adaptation and modification in biology, engineering, the social sciences and popular culture in the 1950s and 1960s, and ended when cybernetics and information theory lost their statuses as universal sciences in the 1970s." Ibid., 6.

presented as (1) privileging ideas of digitization over the scientific concept of information and (2) as using the adjective "cyber" – to elide the particularities of the what he sees as the analogy central to cybernetics: "that all organisms use information-feedback paths to adapt to their environment."[23] This dissertation follows from Kline's discernment of the informational turn, a moment in which Claude Shannon's "A Mathematical Theory of Communication" was interpreted according to certain researchers' objectives and not according to its validity as a theory.[24] Kline writes about the late 1950s:

> In turning to information theory, researchers typically drew on specific aspects of Shannon's theory - such as coding schemas, information measurement and entropy relationships — rather than on the theory as a whole, with mixed results in biology, the social sciences and physics. Researchers in molecular biology spent several fruitless years trying to use information theory to break the genetic "code" before realizing that DNA was not a linguistic code, and therefore not able to be analyzed by Shannon's theory.[25]

The reduction in complexity of Shannon's theory is but one example of the flattening of the discourse of cybernetics during the period leading into and during the Cold War.[26] Kline does not consider how McCulloch's body of work in cybernetic neurophysiology was subject to similar elisions.[27] My investigation of McCulloch is aimed at identifying how our ideas of the brain *prior* to the genetic revolution became subject to new narratives that the discovery of DNA engendered. McCulloch was writing about the brain before and during the period in which the question *What is life?* became supplanted by the question *What is information?* in the history of science and the philosophy of biology.

Steve Heims' seminal account, *The Cybernetics Group*, emphasizes the role of World War II in instituting new norms of interdisciplinarity among natural and social scientists.[28] His chapter "Describing 'Embodiments of Mind': McCulloch and His Cohorts," emphasizes McCulloch's eccentricity and his background in literature. Heims writes that McCulloch "resembled the medieval scientists rather than most modern ones" due to the philosophical

---

[23] Ibid., 6-7.

[24] Ibid., 128.

[25] Ibid., 129.

[26] "One result is that the rich discourse of cybernetics and information theory was flattened in the utopian information narrative." Ibid., 7.

[27] Ibid., 332. See the index of *The Cybernetics Moment* for use of this terminology.

[28] "During the war, both natural and social scientists had typically worked as part of a team, often together with engineers, to address some particular interdisciplinary problem, such as the behavior, fatigue, and maneuvers of an aircraft pilot con- fronted with enemy planes in midair. Researchers came away from these wartime projects with some experience, perhaps even a habit, of interdisciplinary communication and collaboration, as well as a respect for many kinds of machines and their designers." Steve J. Heims, *The Cybernetics Group* (Cambridge Mass.: MIT Press, 1991), 8.

motivations that led him to pursue scientific inquiry.[29] Heims cites McCulloch's own description of his early curiosity about epistemology and cognition, specifically how the questions, "*what is a number that man may know it, and what is man that he may know a number?"* (the title of one of McCulloch's speculative essays)[30] drove his interest in the sciences as an undergraduate at Haverford College. In Heims' character sketches of the main contributors to the American cybernetics movement, McCulloch is cast as a whimsical interdisciplinarian, whose projects are best evaluated in the register of inner reflection on a mechanical world: "Because his style of expression is literary rather than scientific, and terms are not precisely defined, we may see McCulloch's assertions about machines as poetic expressions of his sensibilities in relation to artifacts."[31]

Tara Abraham's recent biographical work, *Rebel Genius*: *Warren S. McCulloch's Transdisciplinary Life in Science*, is a counterpoint to Heims. She provides a brilliant redescription of McCulloch's constant movement between different research circles. Drawing on Judith Butler's notion of performative identity, Abraham argues that shedding and taking on different identities is what in fact made it possible for McCulloch to engage in "the unified and universal rhetoric" that characterizes McCulloch's thinking about the brain.[32] She leaves open the possibility that at the center of McCulloch's life in the sciences is not the brain per se, but instead this traversing of disciplinary boundaries. Her description of McCulloch's movement from neurophysiology to neuropsychiatry is of particular importance for my project. Abraham notes how, during the war period, McCulloch's interest in the brain was also always an interest in the brain's *pathologies*:

> If, prior to this period, McCulloch's interest in scientific foundations and philosophy were peripheral to his laboratory practices on the brain, by now, as he performed the dual identities of neuropsychiatrist and cybernetician, his unique practices of theoretical modeling introspected with his empirical concerns about the diseased brain and its organization.[33]

Abraham's demonstration of the nuances of McCulloch's shifting approaches to the brain opens up a new space of inquiry. As I will argue in this dissertation, it is possible to identify a particular form of *medical cybernetics*, that is, a *therapeutic* neurophysiology that incorporates the central cybernetic concepts of feedback and command-control but is not wholly determined by them. A complete picture of McCulloch's understanding of this new field must include a close analysis of his biological and clinical work concerning living beings. I will approach McCulloch from a new perspective, by focusing on his theoretical and clinical neurophysiology as a way of

---

[29] Ibid., 32.

[30] 22. McCulloch, "Recollections of the Many sources of Cybernetics," 22.

[31] Heims, *The Cybernetics Group,* 38.

[32] Tara Abraham, *Rebel Genius*: *Warren S. McCulloch's Transdisciplinary Life in Science* (Cambridge, Mass.: MIT, 2016), 5.

[33] Ibid., 102.

articulating the complex conceptual system underlying McCulloch's diverse writings and research projects.

It will be useful here to first sketch McCulloch's career in order to see how he merged epistemological questions with experimental and clinical work on the body and the mind, in diverse institutional settings.

As an undergraduate, McCulloch majored in Philosophy at Yale University, graduating in 1923. McCulloch read Peirce, Russell and Whitehead, and Kant (in German); even so, McCulloch located the origin of cybernetics in Descartes.[34] First, because Descartes originated the notion of reflex activity and inverse feedback contained in the animal spirits and their mediation between the muscles and the brain. Second, because McCulloch recognized a conceptualization of coding inherent in Descartes' theory of perception, whereby a series of pulses, varying according to the object they represent, are sent to the brain so the brain can transmit an image, depending on the nature of the pulses, back to the eye.[35] Notably, McCulloch's Masters thesis in Psychology at Columbia University was on the subject of perception, in particular on the aesthetic appeal of certain geometric forms over others. As he wrote: "root rectangles and the Golden Section are aesthetically preferred by most people."[36] McCulloch continued his medical education at Columbia University and completed a residency in neurology and neurosurgery at Bellevue hospital in New York, where patients with Parkinson's disease prompted McCulloch to reflect on the possibility of closed loops in neurological activity: "we wondered whether there was not in them… a vicious circle in the brain."[37]

In 1934, McCulloch joined the Laboratory of Neurophysiology at Yale University, performing experiments involving the compound strychnine in an effort to map the cerebral cortex; this work was done under Dusser de Barenne, who had worked with neurologists Rudolph Magnus and Charles Sherrington and considered himself a Kantian. Before the outbreak of war, McCulloch moved the University of Illinois, to "lay the foundations of" a Department of Psychiatry in the College of Medicine while pursuing his research on carbohydrate metabolism in the brain. In 1941, at a pivotal meeting of the Committee of Mathematical Biology at the University of Chicago, McCulloch met Walter Pitts, the mathematician who would provide the technical skill required for modeling the closed loops of nervous activity, the neurological circuits envisioned by McCulloch.[38] Following two years of collaboration, they co-authored and published "A Logical Calculus of the Ideas Immanent in Nervous Activity," giving birth to the famous McCulloch-Pitts neuron, the core unit of any "neural network." McCulloch met Norbert Wiener in 1943, and was in attendance at the Princeton conferences on cybernetics lead by

---

[34] McCulloch, "Recollections," 25-6.

[35] "This was probably the first coding theorem, and to one familiar with the Morse Code this was particularly appealing. " Ibid., 25

[36] Ibid., 29.

[37] Ibid., 30-1.

[38] Ibid., 35. See Tara Abraham, "(Physio)logical Circuits: The Intellectual Origins of the McCulloch-Pitts Neural Networks," *Journal of the History of the Behavioral Sciences* 38:1 (2002): 3-25.

Wiener from December of 1943 to January of 1944. It is unclear whether Wiener had read "A Logical Calculus" prior to the meeting, but he demonstrated to McCulloch that he was satisfied with the notion of the brain as a digital computer, acceding to the "possibility that it was the temporal succession of impulses that might constitute the signal proper" and not the signals themselves. Following this conference, McCulloch went on to chair ten of the Macy Conferences on circular causal and feedback systems in New York from 1946-1953.[39] John von Neumann, Wiener, Lawrence S. Kubie, F.S.C. Northrop, Walter Pitts, Claude E. Shannon, W. Ross Ashby, were in regular attendance at the meetings; many of these scientists, including McCulloch, attended the Hixon Symposium on cybernetics in 1948. In 1952, McCulloch moved to the Research Laboratory for Electronics at MIT, where he continued work in advanced electrical engineering, once saying: "Modern electrical engineering theory and practice in control, feed forward, interval timing and autocorrelation to bring signals up out of noise bid fair to give us a clear notion of cerebellar activity."[40]

McCulloch's position in the history of cybernetics is prominent. His comment on engineering points to the shared assumption within the field of cybernetics that a signal circulating within a closed feedback loop might be able to regulate other 'control units' and that ultimately, this signal could regulate itself, as a 'control unit' enacting its own organization. This automaticity underlying the cybernetic research program, predicated upon the sending of a signal, has led scholars to attribute the birth of artificial intelligence to the cybernetics movement.[41] More recent work has opened up new inquiries into early cybernetic ideas and their relationship to theories of automaticity, particularly with respect to the nervous system. David Bates cites the interwar work of Kurt Goldstein and Karl Lashley to argue that cybernetic neurophysiology inherited an approach to the brain that saw it as an open system, capable of and always reconfiguring itself to sustain the norms of life, as Georges Canguilhem would say.[42] Similarly, Stefanos Geroulanos and Todd Meyers have identified two issues central to physiology in the early 20th century: first, conflicts over vitalism and mechanism and second, the nature of processes of *organismic integration*.[43] They illuminate the varied historical context for ideas of "adaptation" in the philosophy of medicine and the philosophy of biology, highlighting how

---

[39] "That was in the academic year 1943-1944, and was followed from 1946 on by the 10 Macy meetings on circular causal and feedback systems" Ibid., 40. See Pias, "The Age of Cybernetics" and Heims, *The Cybernetics Group*.

[40] McCulloch, "Recollections," 48.

[41] Paul N. Edwards, *The Closed World: Computers and the Politics of Discourse in Cold War America*. (Cambridge, Mass.: MIT Press, 1997)
and Jean-Pierre Dupuy, *The Mechanization of the Mind: On the Origins of Cognitive Science,* tr. M.B. DeBevoise (Princeton: Princeton University Press, 2000).

[42] David Bates, "Automaticity, Plasticity, and the Deviant Origins of Artificial Intelligence," in David Bates and Nima Bassiri, eds., *Plasticity and Pathology: On the Formation of the Neural Subject* (New York: Fordham University Press, 2015), 194-218. Cf. Georges Canguilhem, *The Normal and the Pathological,* tr. Carolyn Fawcett (New York: Zone Books, 1989).

[43] Stefanos Geroulanos and Todd Meyers. *The Human Body in the Age of Catastrophe: Brittleness, Integration, Science and the Great War.* (Chicago: University of Chicago Press, 2018), 24.

much of this new thinking was a response to the devastating neurological injuries of World War I. They write:

> What occurred in the encounter between researchers and those who escaped death only to live, profoundly transformed by brain injury? More than any literary, philosophical or artistic encounter with brain injury, medical and neurophysiological thought offered approaches that asked detailed questions of the meaning of neurological damage and attempted to grasp what individuality and healing the injured patient could perhaps hope for.

This historical turn entrusted medical and neurophysiological thought44 with not only the practical capacity to organize care for the brain-injured patient but also with an interpretive capacity with respect to notions of individuality and ideals of future life. This turn serves as a point of departure for my project. I will confront McCulloch's research as a truly theoretical neurophysiology, in which theories of the activity of the central nervous system are of philosophical significance; however, not solely with regard to the qualities and organization of the innervation of biological matter (where McCulloch is usually positioned in the history of cybernetics) but also, and equally important, with regard to an individual being's existence in a world that the nervous system helps constitute, so that one can discern and move within an environment. My goal is to present McCulloch's perspective as a reminder to contemporary neuroscience that theoretical questions concerning life, individuality, and experience is not only not at odds with empirical work, and that our conceptions of the microscopic activity of, say, neuronal proteins, glia and cells need to be understood within a framework that is, in its essence, theoretical, because this often implicit framework enacts a certain silent disposition of the individual in the world. This framework, which is always being imagined and interrogated in even the most focused neurological research is, I will suggest, the very material on which neuroscience works.

---

[44] I will offer here a brief comment on the relationship between cybernetics and the history of neurology in America. My project on the cybernetic account of biological life raises the question of how cybernetics might have been incorporated into 20th-century American medicine, how cybernetic principles were put into practice in, say, clinical neurology and psychiatry. Jack Pressman, *The Last Resort: Psychosurgery and the History of Medicine* (Cambridge: Cambridge University Press, 1998) is important in this regard, as a point of reference for understanding the logic of neurology and neurological surgery – how authority to perform lobotomies was rationalized and maintained – in the period in which McCulloch was practicing and conducting experiments. Though the relationship of cybernetics to 20th-century American medicine is a secondary question for me, the possibility of a cybernetic account of biological life is significant because current diagnostic frameworks used in medical practice utilize a definition of brain death that is in very much in accordance with the basic assumption of cybernetics. There are many reasons for this, principal among them the reliance of ICUs and critical care units on machines engineered on the basis of functions first derived by cyberneticists – such machines are programmed to monitor activity, that is, to monitor "life," on the basis of an electrical current such as the Electroencephalogram (EEG). Functional MRIs (fMRIs) are a good counter-example to devices like the EEG, since they rely on radiation to demonstrate blood flow, rather than using electricity to demonstrate nervous activity. Joe Dumit's work on brain death, images and technology is extremely helpful on this point. He explores how techniques and technological metaphors drawn from, say, telegraphs and other electrical systems, ground the very possibility of brain imaging. See Joseph Dumit, *Picturing Personhood: Brain Scans and Biomedical Identity* (Princeton: Princeton University Press, 2004). I am claiming that one answer to this question lies in the 20th-century formulation of the brain-computer analogy, which has its origin in the cybernetics movement, and most notably in the work of McCulloch, a life scientist and neurological clinician.

III. The assumptions of theoretical neurophysiology

In “A Logical Calculus of the Ideas Immanent in Nervous Activity,” McCulloch and Pitts state clearly: “Theoretical neurophysiology rests on certain cardinal assumptions.” The assumptions are a set of ideas believed to be true regarding the cellular components of the nervous system. The first is that “the nervous system is a net of neurons, each having a soma and an axon.” The second and third assumptions regard the synapse and the membrane-voltage necessary for the transmission of a neural impulse: “Their [the neurons’] adjunctions, or synapses, are always between the axon of one neuron and the soma of another. At any instant a neuron has some threshold, which excitation must exceed to initiate an impulse.”[45] As seen in Fig. 1, an image from a 1938 article by McCulloch and de Barenne, one can discern the node-like soma of each cell, the long arm of the axon, and the synapses, the gaps between one cell and another. The image represented the transmission of information from the legs, arms and face to the thalamus, and then to specific cortical regions.

[45] McCulloch and Pitts, “A Logical Calculus,” 343.

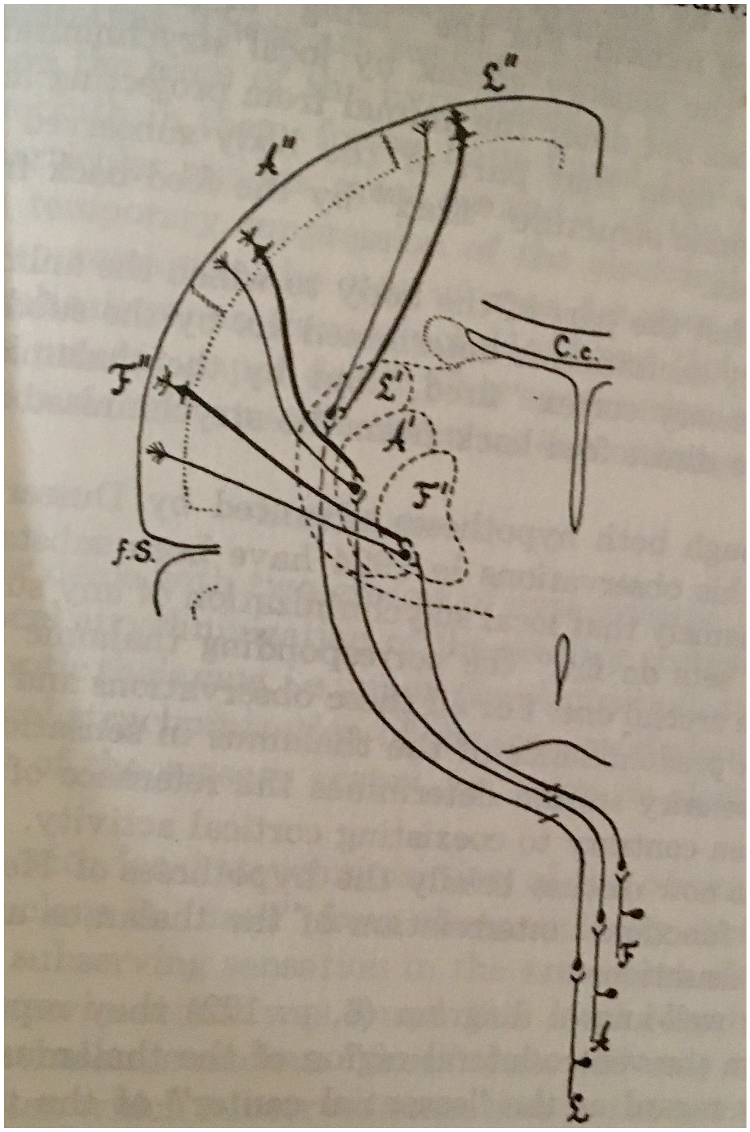


Figure 1

From: Warren McCulloch and J. G. Dusser de Barenne, "Direct functional interrelation of sensory cortex and optic thalamus," *Journal of Neurophysiology* 1:2 (1938): 176-186 Fig. 4 "Diagrammatic representation of the organization of the three main sensory systems (for the legs, arms and face)."

The additional assumptions of theoretical neurophysiology mentioned in “A Logical Calculus” speak to the scale, speed and direction of the nervous impulse: “the impulse is propagated to all parts of the neuron,” “the velocity of the axon varies directly with its diameter,” and “excitation across synapses occurs predominantly from axon terminations to somata.”[46] Accordingly, the McCulloch-Pitts model-neuron possesses certain specific qualities:

1. It is organized with other neurons in a *net*, an unchanging grouping of neurons in which the signal that is the nervous impulse circulates.[47]
2. It participates in nervous activity on an *all-or-none* basis. The signal circulating within a given net is either relayed in its entirety by a member neuron or not at all.[48]

If “A Logical Calculus” emphasized the structure and organization of neural interaction, with links to mathematical notions of computation clear, the paper McCulloch and his colleague John Pfeiffer published several years later, in 1949, proposed an electrical model of the entire central nervous system. The key to this model was the identification of “digital computers” and “brains.” However, crucial to this comparison was the problem of *unity* and *integration*, the relationship between parts and wholes, a problem central to the concept of the organism as McCulloch and others understood it in this threshold moment in the history of biology.

IV. McCulloch’s analogical method and Kant’s natural law

In “Of Digital Computers Called Brains” nervous activity is considered circuit action in the working hypothesis that we can imagine “the anatomy of the nervous system as if it were a wiring diagram”[49] so as to clarify how the components of the nervous system work,[50] and how the activity of the nervous system contributes to human behavior as well cognitive processes, specified here as thinking and knowing. McCulloch and Pfeiffer begin with a description of the role of “the concept of ultimate units” in the fields of biology, physics, and genetics and then apply the concept of ultimate units to the field of *communication*.[51] The field of communication

---

[46] Ibid., 343

[47] “But for nets undergoing both alterations, we can substitute equivalent fictitious nets composed of neurons whose connections and thresholds were unaltered.” Ibid., 345.

[48]“The activity of the neuron is an all-or-none process.” Ibid., 346.

[49] Ibid., 369.

[50] “For our object is to set up working hypotheses as to the circuit action of the central nervous system as a guide to further investigation of the function of its parts, and as a scheme for understanding how we know, think and behave.” Ibid., 369.

[51] “But the concept of ultimate units had its first bearing on modern scene when the discovery that gases combined chemically by volume in the ratio of small whole numbers marked the transition from alchemy to chemistry.” Ibid., 368.

is quantized with the unit,[52] the signal in the same way that the other fields have been quantized by the units of the cell, atom and gene, respectively:

> One of the most important notions that has proved its value in many sciences may be traced back to the atoms of Democritus. But the concept of ultimate units had its first bearing on modern science when the discovery that gases combined chemically by volume in the ratio of small whole numbers marked the transition from alchemy to chemistry.[53]

Alchemy became chemistry when it was discovered that the volume of combined gases could be calculated on the basis of small, whole number ratios - such quantization of gases implies the existence of an ultimate unit within the field, chemistry, that renders matter analyzable, countable – one example the paper offers is of Avogadro, calculating how many molecules exist within a 1 gram-molecular weight.[54] As argued by McCulloch and Pfeiffer, the "ultimate unit" gives a scientific field a method on the basis that, on some microscopic scale — some ultimate scale – nature is *indivisible*. If there exists a level at which nature is indivisible, then there are indivisible parts of each whole*, capable of explaining the whole's function*. I argue that need to see cybernetics as an inquiry in mereology (the philosophy of "part" and "whole") in the terms of communication engineering. [55]Cybernetics was, that is, an effort to describe part-whole relations in the complex system of the organism[56] with recourse to exemplars of postwar technology – in particular electronic circuitry[57] and new digital computing machines.[58] The challenge was the identification of the fundamental elements of both technical and living systems.

This tension within in cybernetics was already at issue in Kant's prescription of any possible science of the organism in *The Critique of Judgment*. McCulloch was thoroughly

---

[52] "All communication is a matter of information conveyed by signals, and the next great step was atomic signals." Ibid., 368.

[53] Ibid., 368.

[54] "Unless you compare the writings before Dalton proposed the atomic hypothesis and before Avogadro computed the number of molecules per gram molecular weight with all that comes after- wards, it is difficult to appreciate how great a revolution this idea can produce in any science." Ibid.

[55] Steve Heims describes Weiner's synthesis of cybernetics as an attempt to link Augustinian theology to cybernetic science and describes his effort: "the predominant idiom, nevertheless, of his unification was that of communication engineering" Heims. *The Cybernetics Group,* 249.

[56] The verb "describe" is used in both "Of Digital Computers Called Brains" and "A Logical Calculus," when the authors give an account of what they hope to achieve with respect to their analysis of the nervous system.

[57] "All of this group was interested in models of the brain based in electronic circuitry and inclined to mechanistic philosophy." Heims, *The Cybernetics Group*, 12.

[58] Heims, in a discussion of von Neumann's presentation at an early Macy Conference (March 1946), also uses the verb "describe": "The morning of March 8 was devoted to a description of the workings of general-purpose electronic digital computers by John von Neumann, the leading designer in the country of the logical structure of these yet-to-be-built computers.." Ibid., 19.

familiar with Kant, and a brief engagement with the Kantian perspective on the organism can help articulate the broader concerns of McCulloch's own philosophical and epistemological reflections. Following his description of the antimony of teleological judgement in his Third Critique, Kant forecloses the possibility that we will inhabit a scientific future in which the inner workings of the matter composing a biological unity will ever become known to us.[59] It is the fact that the antimony of teleological judgement is only resolvable by a judgement that *reflects* and does not determine, that makes obvious the encounter of biological functions as solely a cognitive project and not the object of a true science: "When a judgement determines it has no principles of its own that form the basis for *concepts of objects*"[60] – a determining judgement depends on the clear reality of an external law, and we have no ability to arbitrate on the truthfulness or not of any given first maxim, any given a priori principle: "Reason however cannot prove either of these two principles because we cannot have a determinative a priori principle for the possibility of things in terms of merely empirical laws of nature" (267). We should understand merely empirical laws of nature, motive force, and mechanical law as interchangeable in the Third Critique. "We have no insight into the first inner basis responsible for the endless diversity of the particular natural laws, because they are contingent for us since we cognize them only empirically, and cannot possible read the inner and completely sufficient principle of the possibility of nature (this principle lies in the super sensible)" (269)

I see this problem of natural law as the key Kantian problem raised by McCulloch's work, in contrast to most scholars, who argue, as Michael Arbib does[61], that relationship of the universal to the particular as explicated in *The Critique of Pure Reason* (the connection, say, between "a particular wheel and the pure geometrical concept of a circle"[62]) was the Kantian issue addressed in McCulloch's mereological inquiries. Arbib notes how McCulloch and Pitt's paper "How We Know Universals" (1947) offers "a theoretical construction of neural networks for pattern recognition that shows how visual input could control motor output via the distributed activity of a layered neural network," offering McCulloch and Pitts' model as an example of how perception is linked to action via nervous activity.[63] While I recognize the significance of this problem, I will show how McCulloch's medical and biological cybernetics makes the body discernible in the physical world, while simultaneously complicating that project, as he observes how the physical and chemical processes that maintain the body's organization in fact always extend beyond the body, into a world that the body actively engages in, albeit in a limited way.

---

[59] The organism, existing in Kant's terms as a "unity," is not possible from mechanical operations alone: "For then, the unity that is the basis on which natural formulations are possible would be only the unity of space , and yet space is not a basis responsible for the reality of products but is only their formal condition; space merely resembles the basis we are seeking inasmuch as no part in space can be determined , except in relation to the whole." (293). Kant, Immanuel, and Werner S. Pluhar (trans.) *Critique of Judgment*. Hackett Pub. Co., 1987.

[60] Immanuel Kant, *Critique of Judgment,* tr. Werner S. Pluhar (Indianapolis, Ind.: Hackett, 1987), 265

[61] Michael A. Arbib, "Schema Theory: From Kant to McCulloch and Beyond," in Roberto Moreno Diaz and Jose Mira-Mira, eds., *Brain Processes, Theories, and Models: An International Conference in Honor of W.S. McCulloch 25 years after His Death* (Cambridge, Mass.: MIT Press, 1996), 11-23.

[62] Ibid., 14

[63] Ibid., 13.

What McCulloch renders clear is that the chain of events that constitutes an organism's response to the world – (1) the stimulus (2) a signal's movement to the central nervous system (3) a signal's movement from the central nervous system to the peripheral nervous system resulting in an (4) executed response – are in relation to both the internal values of the organism and natural law.[64] The impulse and the response it carries, constituted by intricacies of physical and chemical interactions and the immutable parameters of electricity (e.g. positive and negative charge) go towards a world constituted by matter that possesses *the same tendencies* while being unfettered by the biological requirement of perpetually obtaining an organization that will resist degradative effects of entropy. The degradative effects of entropy are not uniquely observed in living organisms; however, degradative effects of entropy represent the consummate threat to life. How does one then perceive a world that has an invariant status but where the norms for life are not given in advance? How to build that world when there is no procedure that is predictable? And how does one then respond to one's own world building when one has successfully altered the world from the world of a previous instance of perception? The nervous system facilitates encounters with a world *formed and in the process of being formed*, and so this perceptual concept of life in McCulloch's work becomes inseparable from concepts of time. The mathematical models submitted in "A Logical Calculus" use the parameter *t*, time, and so the activity of the neurons in nervous nets has, as its *primary relationship*, a connection to time. Understanding nervous activity in relation to time also makes comprehensible the *changes* in the world that one has created. Work on the matter of the world, conditioned by the physical and chemical requirements of natural law, is as an indelibility, a physical, electrical impression that registers (if only fleetingly) in time in the neurons that light up in response to it.

In cybernetics, knowledge is evaluated for the degree of predictability it offers. Mathematical as well as analogical models for nervous activity offer a description of the organism as a state reproducing itself.[65] The "Note by the Editors," which prefaces the transcription of dialogue at the Macy Conference of 1951, presents the centrality of the conceptual model to the cybernetics movement,[66] noting the ability of certain models to be transposed across different scientific fields, "all the members have an interest in certain conceptual models which they consider applicable to problems in many sciences"[67] as well as the ability of certain conceptual models to serve as the *lingua franca* of science, where models serve as "fragments of a common tongue likely to counteract some of the confusion and complexity of

---

[64] McCulloch and Pitts refer to internal standards of value in the discussion of the neuron in "A Logical Calculus," 343.

[65] "A state reproducing itself, like an organism, or a social system in equilibrium, or a physiochemical-aggregate in a steady-state, defied analysis until the simple notion of one-dimensional cause and effect chains was replaced by the bidimensional notion of a circular process." Heinz von Foerster et al., "A Note by the Editors," in Pias, ed., *Cybernetics: The Macy Conferences*, 343.

[66] "All the members have an interest in certain conceptual models which they consider applicable to problems in many sciences." Ibid., 342.

[67] Ibid.

… (scientific) language."[68] Again, the cybernetic conceptual model is similar to the Kantian Judgement that can only reflect and not *determine*. Judgement, in Kant's system, mediates between Understanding and Reason.[69] Judgement possesses "an a priori principle of its own" in purposiveness,[70] such that the "concept of a purposiveness in nature"[71] makes possible the connection between what is presented to the mind through the legislations of Reason and Understanding. It is the concept of purposiveness specifically arising in nature, provided by Judgement, that is our only recourse to cognize biological activity. This concept of purposiveness, when applied to the organism, elides the particularity of the organism's parts, denying the parts a teleology that is reserved for our cognizing of the organism as a unity. What is connoted by description in "Of Digital Computers called Brains" differs from what is connoted by description in the Third Critique, but the antithetical concepts are shared. What is antithetical to the description of the organism's parts as participants in the teleology accorded to the whole is the understanding of the "truth" of the organism's parts, that incidentally compose a whole, in and of themselves. In cybernetics, a "true" knowledge of natural law is supplanted by the goal of improving the accuracy of the prediction the model enables.

Returning to the "Note by the Editors" of the 1951 Macy Conference, there are two conceptual models important for cybernetics: the theory of information, and the notion of circular causal processes, "now closely allied to information theory." The biological example of the first is the gene, "as an organic template somehow providing for its own production and governs the building of a multicellular organism from a single cell,"[72] while the biological example of the second is the organism as perpetuating within a steady state that is self-reproducible *on the basis of perception*: "Many of these processes (the complex self-regulatory processes which guarantee a relative constancy of blood sugar level, osmotic pressure of hydronium ion concentration, or of body temperature) are at least partially understood … but we know next to nothing of the physiological functions which underlie our perceptual constancies." Explaining what is meant by perception in this context, the authors note:

> Normal perception is reactions to relations, to universals such as size, shape, and color. Perceived objects tend to remain invariant in their size while distance form the observer varies; perceived shapes and colors retain subjective identity in varying positions and and under varying illumination.…recent attempts at identifying a possible neural basis for our reactions to universals have adduced hypothetical sustained activity in neuronal circuits

[68] Ibid. And they also note: "The concepts suggest a similar approach in widely divers situations; by agreeing on the usefulness of these models, we get glimpses of a new *lingua franca* of science, fragments of a common tongue likely to counteract some of the confusion and complexity of our language." (Ibid.)

[69] "And yet the family of our higher cognitive powers also includes a mediating link between understanding and reason. This is *judgement* about which, we have cause to support by analogy , that it too may contain an a priori, if not a legislation of its own, then at least a principle of its own, perhaps a merely subjective one, by which to search for laws" Kant, *Critique of Judgment,* 16.

[70] Ibid., 18.

[71] Ibid., 36-37.

[72] Von Foerster et al., "A Note by the Editors," 343.

> as one of the prerequisites for the central processes which guarantee perceptual constancies.[73]

So the electrical model of the brain offered in "Of Digital Computers Called Brains" is explicitly understood as a thought experiment that, in its analogical power, would clarify the biological processes of cognition, specifically the cognitive processes of thinking and knowing. The key concepts of thinking and knowing in McCulloch's medical and biological variant of cybernetics will rely on a concept of perception, which, in its depiction as a delivery of a body to a world, will grant causative power to thinking and content to knowing. McCulloch and Pfeiffer's electrical model of the nervous system, in other words, does offer a model of cognition in relation to the technologies of computation, but it is in essence a model of the cognition of *perceptual constancies,* something that could not be extricated from the biological purposes of living beings in particular environmental conditions.

V. Cybernetics and the life-question in philosophy of biology

McCulloch discusses cybernetics as one branch of the science of signals, whose project was "to analyze all purposive behavior in terms of inverse feedback."[74] In McCulloch and Pfeiffer's electrical model of the brain, the neuron is represented as the component relay of a computing machine,[75] leaving the bit – the presence or absence of a neural impulse configured in the terms of a binary digit – as what constitutes the signal.[76] The cyberneticists are not characteristically studied for their influence on biological and medical concepts. Instead, as discussed in section II above, the cyberneticists are looked to for their influence on the theory of information, the theory of neuroplasticity, the development of artificial intelligence, and the development of digital computing. However, other authors have focused on cybernetic conceptions of life. Evelyn Fox Keller, for example, in *Refiguring Life: Metaphors of Twentieth-century Biology,* traces the influence of cybernetics on the genetic program, a concept of self-organization and gene expression offered in Francois Jacob's *Logic of Life*, foregrounding the boundary in the history of biology between the focus on the cellular organism in pre-1960s biology and the genetic revolution that has characterized subsequent biological research. Lily Kay describes the McCulloch-Pitts neuron in relation to von Neumann's theory of self-reproducing biological automata, a theory of life positing that proteins, understood as microscopic machines, can

---

[73] Ibid., 344.

[74] McCulloch and Pfeiffer, "Of Digital Computers Called Brains," 372.

[75] "Thus regarding the anatomy of the nervous system as if it were a wiring diagram and the physiology of the neuron as if it were a component relay of a computing machine, we shall describe the brain in terms thoroughly familiar to the electrical engineer whose business is communication." Ibid., 369.

[76] In the simplest case, this reduces to the presence or absence - call it one or zero - of something at an appointed place or time. This is the famous binary digit now nicknamed "bit" Ibid., 368.

assemble other proteins of increasing complexity.[77] My own interest in the cyberneticists, McCulloch foremost, lies in their influence on concepts predominant in the first half of 20th-century biological science, when the question *What is life?* was not tied to contemporary notions of the representation and reproduction of *information* in the gene. “The image of a genomic ‘Book of Life’—laden with biblical resonances — emerged in the 1960s and now animates the human genome projects, which are so often viewed as a mammoth task of information and word processing.”[78] There are concepts of life in McCulloch’s work that should be understood separately from the genetic concept of life that characterizes research in late 20th century biology. McCulloch’s life-concepts — which will be studied in Chapter 1 in terms of perception, Chapter 2 in terms of cure, and in Chapter 3 in terms of a chemical and physical reaction — either pre-date or complicate the modern genetic concept of life. McCulloch’s notions of biological life, derived from his study of the nervous system at different scales, serve as a precursor for — or even as a productive heuristic for reading — the modern genetic concept of life.

My project understands McCulloch as unique among the cyberneticists, not just for his ability to reform scientific disciplines,[79] not for his ability to understand the difficulty of using a model – a universal – to describe embodied reality,[80] and not for the rarefied philosophical motivations of his research,[81] but rather for his specific training and practice as a *physician*, which conceptually and practically equipped him to move between scales in his assessment of cognition, neuropathology, and curative therapy. The question of movement between scales of analysis is also a question of mereology, a question of identifying the nature of the whole in different spaces, and different forms of organization. I am proposing that McCulloch’s model of the brain, which derives a theory of perception from the structure of the central nervous system, is also an explanation of the existence of biological *life* – it is a an origin story, a tracking of a causal order from the initial moment when organisms appear and develop, and are then able to persist and reproduce as biological wholes.

Of course, the nervous system is not traditionally one used to derive core *physiological* concepts. The neuron, as a category of cell, is singular among cell types in vertebrate physiology due to its structure and due to the fact that it cannot divide in order to regenerate.

---

[77] Kay writes: “In broaching biological automata von Neumann pared down the problem of living organisms into two parts: (1) the functioning of their elementary units; and (2) the system (logical, organizational, or other) by which these parts are assembled.” Lily Kay, *Who Wrote the Book of Life?: A History of the Genetic Code* (Stanford: Stanford University Press, 2000), 109.

[78] Ibid., xv.

[79] As Abraham argues in *Rebel Genius*.

[80] As Katherine Hayles maintains: “I admire McCulloch because he made the audacious leap from amorphous tissue to logical model; I admire him even more because he resisted the leap.” And furthermore: “But unlike other logicians … he refused to leave embodied reality behind.” N. Katherine Hayles, *How we Became Posthuman: Virtual Bodies in Literature, Cybernetics and Informatics* (Chicago: University of Chicago Press, 1999), 62, 60.

[81] As Heims often emphasizes: “Probably no other neurophysiologist in the 20th century talked so much about the views of St. Bonaventura, Duns Scotus, William of Occam, or Peter Abelard.” Heims, *The Cybernetics Group,* 32.

Still, McCulloch presents the brain as the physical structure best suited for the circuit action that constitutes the cognitive processes of thinking and knowing.[82] One of his students discussed McCulloch's research on the brain, first using an analogy with the kidney – "If one were to get a book on the kidney that never once mentioned urine or the production of urine, one would feel cheated" – and then with the muscle – "If one had a long essay on the muscle which never once mentioned contraction, then one would feel cheated." McCulloch approached cognition, then, as a *physiological* function suited for the brain, in the same way the production of urine is an activity suited for the kidney, and contraction for the muscle. How "the anatomy and physiology of the nerve" facilitates cognitive activity was the central question in McCulloch's work.[83]

In the essay "Of Digital Computers Called Brains*,"* McCulloch and Pfeiffer submit that cognition is the transmission of discrete signals occurring either as neural impulses in the organ, the brain, or occurring as the processing of code in a digital machine. Cognition, for McCulloch, is therefore not an activity limited to biological organisms. In that essay, the authors refer to ENIAC (the Electronic Numerical Integrator and Computer, at the Ballistics Research Laboratory in Maryland), and the differential analyzer (an analog computer at MIT) in an explicit comparison with the cerebral cortex.[84] However, the goal of McCulloch's own research in cognition was not "technical" but instead primarily *physiological*, to understand, that is, how the anatomy of the central nervous system, and the particular anatomy of the brain, was of such a kind that it could *achieve* the function of cognition. His was an explanation of cognitive activity that constantly referred to the anatomical structures that compose the brain precisely because the quality of thought and perception was never abstract, but always integrated into living, organized beings. In light of this, my study of McCulloch's influential cybernetic representation of the brain and its activity will draw heavily on his early work in neuroscience, where the theoretical distance between matter and activity, between structure and force, between clinical and conceptual practice, all speak to the confounding fact that an organism's physical existence can somehow coincide with its ability to *know*.

VI. Experimental epistemology

The formal description of nervous activity submitted in the essay "A Logical Calculus" is inherently epistemological. The description of nervous activity is a matrix function for how we, as physical extensions of matter, might be able to come to know a function of knowing. The structure that we use to inquire is the structure he inquires into, where the brain, as object of study is what is responsible for any study undertaken and any apprehension of the world. Perception is the central problem of epistemology for McCulloch — and I claim it is the central problem in McCulloch's response to the life-question.

As is well known, McCulloch authored several texts on the subject of epistemology,

---

[82] On circuit action: "The treatment of nets which do not satisfy our previous assumptions of freedom from circles is very much more difficult than that case. This is largely a consequence of the possibility that the activity may be set up in a circuit and continue reverberating around it for an indefinite period of time." McCulloch and Pitts, "A Logical Calculus," 352.

[83] Jerome Lettvin, "Introduction to Volume I," *Collected Works,* 1:7.

[84] 374. McCulloch and Pfeiffer, "Of Digital Computers Called Brains," 374.

including “Knower, Known and Knowledge,” the famous essay “What is a number that man may know it, and man, that he may know a number,” and “Through the Den of the Metaphysician,” which includes a reflection on Heraclitus and Zeno of Elea. An anecdote related by one of his colleagues reveals that on the door to McCulloch’s lab at the University of Illinois was a sign “Laboratory of Experimental Epistemology.”[85] Why did McCulloch think of his work in this way?

The transmission of a neural impulse depends on the existence of a voltage across the cell membrane. The membrane potential of a neuron in a resting state is -70 mV. The signal carried by neuron, the signal transmitted from the presynaptic neuron to the post synaptic neuron is a depolarization event called an Action Potential. The transmission of a neural impulse is (1) unidirectional and (2) irreversible. The transmission occurs in one direction down the length of the axon and the transmission cannot go backwards: once the change in charge reaches the synaptic terminals, due to the mechanics of voltage-gated and ligand-gated channels involved in depolarizing the cell, the charge is static.

The neural impulse is only transmitted down the length of the axon upon the summation of stimuli achieving a certain value. This is a key point, there is a threshold value below which the action potential will not be generated. This value is positive, meaning, at the moment the neural impulse is generated the cell has experienced a specific change in charge with respect to its environment.

McCulloch knew this,[86] and it is this awareness of the threshold voltage of the neural membrane necessary for the transmission of an impulse that informs the central assumption of “A Logical Calculus” and “Of Digital Computers called Brains”: that a formal representation of cognition is possible because the transmission of a neural impulse is an ‘all or none value’ – stated in the following terms : “the ‘all-or none’ law of nervous activity is sufficient to insure that the activity of a neuron may be represented by a proposition.”[87] By “activity of a neuron” what is meant is the depolarization event transmitted across vital tissue – it is the physical fact of a transmission through matter that is presumed to be in an identity relationship with the function derived in the paper. It is the matching of relations of the flesh to value: “physiological relations existing among nervous activities correspond, of course to relations among the propositions.”[88]

McCulloch approximated the arrangement of neurons by a “net,” and the central problem of a paper such as “A Logical Calculus” was how to “calculate the behavior” of any given net, and how to functionally derive a net that behaves always in the same way.[89] The two goals are the same, but with differential emphasis on the universal in one instance and the particular in the

---

[85] McCulloch, “Recollections,” 23

[86] “[A]t any instant, a neuron has some threshold, which excitation must exceed to initiate an impulse . this, except for the fact and the time of the occurrence, is determined by the neuron , not by the excitation.” McCulloch and Pitts, “A Logical Calculus,” 343.

[87] Ibid., 359.

[88] Ibid.

[89] “Materially stated, the problems are to calculate the behavior of any net; and to find a net which will behave in a specified way, when such a net exists.” Ibid., 347.

other — but still, the functionality of the model is dependent on the ability of the neuron to establish value. Another assumption of the "A Logical Calculus" is that an action potential exists for each neuron and the stimulus has no effect on the establishment of this threshold: "at any instant, a neuron has some threshold, which excitation must exceed to initiate an impulse. This, except for the fact and the time of the occurrence, is determined by the neuron, not by the excitation."[90] The claim that the neuron establishes the threshold of its own excitation means that it is a quality of matter to include a standard of value. If inherent in the neuron is the evaluation of charge necessary to generate an action potential – if the value is *independent* of the stimulus, *independent* of the introduction of charge, then there is some relation between function and physiological form left unmodeled in McCulloch's system. The arrival of value is left unaccounted for. Moreover, we're made to describe the matter of the cell apart from its primary function, and we begin to understand the possibility of a physiological form being suited to a multiplicity functions, some of them functions in the dark, like here, the production of a standard of value, that takes place apart from our description of it.

And yet, at the center of McCulloch's work is the attempt to demonstrate that reality is knowable to us, even reality considered as an activity, reality defined as the relations between the components of our internal physiology. It is not a question: whether we can attribute certain definite postulates to the real. It is a question of what postulates we choose to model at a given time. There are a variety of ways McCulloch broaches this question: (1) the nervous system is what "intervenes" between the inside and external world;[91] (2) the parameters are used in McCulloch's models are both universal and physical; (3) nervous activity is both the function of a physiological organ and the means by which knowledge is possible. In fact, at times reality itself hinges upon our ability to describe it:

> Thus, empiry confirms that if our nets are undefined, our facts are undefined, and to the real, we can attribute not so much one quality or 'form'. With determination of the net, the unknowable object of knowledge, the 'thing in itself' ceases to be unknowable.[92]

The neurons modeled in nervous nets in linear and closed loops, do the work of facilitating reality's achievement of form. A reality in which relations are cultivated between its components is contingent upon the ability to define the net, to determine the net, to achieve a formal representation of the net's activity - for example, the modeling of the sensation of a cold object put to the flesh.[93]

With the formal representation of nervous activity, the 'thing in itself' appears to become knowable — here we can allude to the PreSocratic philosophers, like Anaxagoras, that McCulloch studied in that the achievement of Mind [*Nous*] is the act of crisis, as decision and separation, the ability to cleave reality into forms comprehensible to us. In the cybernetic context, the problem if complicated because Mind is encountered not a substitute for the divine

---

[90] Ibid., 343.

[91] "The role of the intervening nervous net as what is depended upon for the correspondence between perception (internal) and the 'external world'" Ibid., 350).

[92] Ibid., 359.

[93] Ibid., 350.

"one" but as itself an object. Mind, the "thing in itself," is what is rendered clear, and the means by which we are able to achieve clarity. This point is not lost on McCulloch, and in fact his epistemological texts can be read as response to the fact *we* obtain a material existence, so we need to explain matter's activity on a body we claim as ours. It's a matter of possession or ownership included in a reflection on matter in comparison with matter's activity.

The model in "A Logical Calculus" makes plain the function unique to a physiological object, but because that function is cognition, because that function is thinking, to formally represent nervous activity is also to represent how we know the object whose structure gives it the means to know. This is knowing as a physiological function suited for the organ, the brain. A consequence of this description of nervous activity is, in a revelation of object and method, an answer to the questions that arrive in tandem: how the brain works and how we know how the brain works. Knowing how an organ engages in physiological activity, and the physiological activity that is the transmission of a neural impulse are the *same activity*. The model is the articulation of knowing – knowing, or knowing that which knows.

To identify the definition of life immanent in McCulloch's biological and medical cybernetics, I will in this thesis develop McCulloch's multiple engagements with the idea of world-building. This broader concern will, I hope, help elucidate his epistemological approach, his belief that thinking is the tool from which the function of thought is derived. McCulloch was acutely aware that we live the experience of a conflict, the conflict immanent in a perpetual adjustment of focus in our perception of the world and of ourselves. Our very phenomenal experience *depended* on the disparity between the assumption of a distance between us and the objects we reflect on, and the realization that the object we reflect on is in fact *the very means of reflection;* the world of experience is both the material and efficient cause, our matter and our activity, such that the distance collapses in on itself. And we experience this all the time, the building up of analytical distance and the realization that we cannot liberate ourselves from the concrete activity and forms of our own thought. The relationship between matter of different kinds, neuronal on the one hand and non-neuronal on the other, was what complicated the part-whole problem in the context of McCulloch's philosophical, technical, and medical approach to biology, allowing him to reconfigure the boundaries of the organism. The organism's *responses* to the world, facilitated by capacities of nervous tissue, in fact *comprise the world*; the way that the environment impresses itself upon the organism, again facilitated by nervous tissue, are themselves *of the organism*.

Chapter 1: Perceptual life in "Of Digital Computers Called Brains"

I. Introduction

In this chapter, I will argue that a rhetorical analysis of the treatment of the body and nature in "Of Digital Computers Called Brains" reveals that the neurophysiology of visual perception implies a concept of biological life. I address the technical aspects underlying McCulloch and Pfeiffer's imagery to identify the main concepts of a biological and medical cybernetics, where the structure of the body's sensory, perceptual capacity is what makes possible the body's capacity for the transmission and encoding of information. Importantly, their paper precedes James Watson and Francis Crick's "Molecular Structure of Nucleic Acids: A Structure for Deoxyribose Nucleic Acid," the first publication announcing the discovery of DNA. Here, we will look at the cybernetic body's relationship with information on a macro scale, where is externalizes and de-corporealizes "information." McCulloch and Pfeiffer's body is not *constituted* by information but rather creates it in the form of the material changes inherent in any response to the world. With close attention to the description of the eye in "Of Digital Computers Called Brains," I will argue that the analysis of visual response shows that "vision" here is not the mere transformation of information from light ray to eye, but rather, a way in which a world is built for the organism.

McCulloch and Pfeiffer's electrical model of the brain, along with the conductivity and impressibility comprised within that model, require a cognitive faculty that occurs in time*;* a concept of life in their account of the central nervous system and how a world is capable of both bearing and preceding the body's response to it. I claim that perception is what the activity of the electrical model is *for*, conditioned by the laws of physics, which function as natural law.

II. Perception as a problem in American Cybernetics

"Of Digital Computers Called Brains" outlines a set of hypotheses capable of explaining the "circuit action of the central nervous system," the simultaneously electrical and biological activity of the central nervous system that results in cognition:

> For our object is to set up working hypotheses as to the circuit action of the central nervous system as a guide to further investigation of the function of its parts, and as a scheme for understanding how we know, think and behave.

The electrical model of the brain in "Of Digital Computers called Brains" is offered as a thought experiment. The thought experiment is as follows: "Let us replace each neuron…(with) a relay having its own battery, charged by a series of chemical reactions converting sugar and oxygen to carbon dioxide and water."[1] Each neuron is replaced by a switch capable of opening or closing

---

[1] Warren McCulloch and John Pfeiffer, "Of Digital Computers Called Brains," *The Scientific Monthly* 69:6 (Dec., 1949), 369.

progressive circuits based on a variation in current.[2] It is postulated that grasping the components – the parts – of the central nervous system will bring the ability to better understand the physical conditions for how we know, think, and behave. In McCulloch and Pfeiffer's paper, the parts of the central nervous system are analyzed according to post-war frameworks of electrical engineering and communications technology. On the subject of the action potential and the language of post-war communications technology, physiologist Ralph Gerard offers the following, from a paper given at the 1950 Macy Conference.

> The language, experience, and ways of thought, say, of communication engineering seem to be admirably adapted to make us recognize explicitly that the nerve impulse is not merely some physical-chemical event but a physical-chemical event carrying meaning. It is therefore a sign or signal, as the case may be; and this is very important in physiological thinking.[3]

The meaning Gerard identifies is in relation to a brain with interpretive capacity. "Of Digital Computers Called Brains" is a paper on the structure underlying thought and the question of intelligence – artificial intelligence – is addressed from a physiological-structural perspective. When considering a machine and its use of vacuum tubes instead of cells, neurons, McCulloch and Pfeiffer consider the size and power of the machine – "[it] would require Niagara's power to run it"[4] – in the register of the absurd; even so, McCulloch and Pfeiffer cite Alan Turing's article on "Computing Machinery and Intelligence." If we turn to Turing's "Intelligent Machinery," an unpublished text of a talk presented in 1948, Turing argues that it would be possible one day to manufacture machines with intelligent behavior and that human beings themselves model the process of self-modification, through the interference, contact and education, that makes the machine's training possible.[5] As Turing notes: "the cortex of the infant is an unorganized machine, which can be organized by suitable interfering training. The organizing might result in the modification of the machine into a universal machine or something like it."[6] For Turing, the

---

[2] "Let us replace each neuron by a relay having its own battery, charged by a series of chemical reactions converting sugar and oxygen to carbon dioxide and water. When the supply of these materials fails, or the reactions are obstructed, the voltage of the relay ceases to be in the proper range, and the circuit action goes wrong in any one of many ways." Ibid.

[3] Ralph Gerard, "Some of the Problems Concerning Digital Notions in the Central Nervous System," in Claus Pias, ed., *Cybernetics: The Macy Conferences 1946-1953* (Zurich and Berlin: Diaphanes, 2016), 171.

[4] McCulloch and Pfeiffer, "Of Digital Computers Called Brains," 370.

[5] "Training" is Turing's word: "A human mathematician has always undergone an extensive training. This training may be regarded as not unlike putting instruction tables into a machine." Alan Turing, "Intelligent Machinery," in B. Jack Copeland, ed., *The Essential Turing: The Ideas that Gave Birth to the Computer Age* (Oxford: Oxford University Press, 2004), 394.

[6] Ibid., 438. See David Bates, "Automaticity, Plasticity, and the Deviant Origins of Artificial Intelligence," in David Bates and Nima Bassiri, eds., *Plasticity and Pathology: On the Formation of the Neural Subject* (New York: Fordham University Press, 2015), 194-218.

universal machine, the *universal logical computing machine*, is a discrete machine.[7] This subclass of discrete machine is a machine capable of interpreting symbols one-at-a-time as etched on a tape run through it —a tape that was printed by another machine.[8] McCulloch and Pfeiffer's notion of the digital is related to the notion of switching between discrete, identifiable states[9]. At a given time, Turing's universal logical and discrete machine operates only according to the symbol scanned. With regard to the tape and the machine's activity, the tape can be manually moved back and forth to cause the machine to assume different processes. For Turing the brain is similar to a discrete machine[10] and nerves are similar to electrical circuits in that "they are able to transmit information from place to place, and also to store it." Instead of replicating man outside of himself, part-by-part, Turing suggests building a brain without a body:

> Instead we propose to try and see what can be done with a 'brain' which is more or less without a body, providing at most organs of sight, speech, and hearing. We are then faced with the problem of finding suitable branches of thought for the machine to exercise its powers in.[11]

The branches considered are: games, language, cryptography and mathematics.[12] Turing discusses how games and cryptography are the most suitable branches of thought of all for the machine, the brain-without-a-body, as they require "little contact with the outside world." For chess, though, Turing notes that the machine would still require eyes.[13] Visual perception was deemed necessary for the machine, and eyes, the only organs it is afforded.

Visual perception was a key problem of neurophysiology in the mid 20th century as well as during the interwar period. Karl Lashley, at Harvard's Psychology Department, wrote a summary of his research on the retina, the nervous system, and light as a stimulus, in 1938.

---

7 "We may call a machine 'discrete' when it is natural to describe its possible states as a discrete set, then motion of the machine occurring by jumping from one state to another." Ibid., 412.

8 "It is possible to describe L.C.Ms [Logical Computing Machines] in a very standard way, and to put the description into a form which can be 'understood' (i.e. applied by) a special machine. In particular it is possible to design a 'universal machine' which is an L.C.M. such that if the standard description of some other L.C.M. is imposed on the otherwise blank tape from outside, and the (universal) then set going, it will carry out the operations of the particular machine whose description it was given." Ibid., 414.

9 "Now, since the world is composed of particles which can only be in discrete states, we could treat all machines as if they were digital devices if we could make fun use of all these particles in their states." McCulloch and Pfeiffer, "Of Digital Computers Called Brains," 369.

10 See the chart in Turing, "Intelligent Machinery," 412.

11 Ibid., 420.

12 "The following fields appear to me to have advantages i.) various games e.g. chess, noughts and crosses, bridge, poker ii.) the learning of languages iii.) the translation of languages iv.) Cryptography v.) Mathematics." Ibid., 420.

13 "For instance in order that the machine should be able to play chess its only organs need be 'eyes' capable of distinguishing the various positions on a specially made board, and means for announcing its own move." Ibid., 421.

Lashley explains, with reference to the notions of figure and ground of the Gestalt school, the crucial concept of unity, and its role in visual perception:

> Figure is generally described as something perceived as coherent and unitary in contrast to ground, which is some- what lacking in this property. We cannot, of course, apply such a subjective definition in comparative studies but, if we seek a definition of unity in perception, we may reach an objective expression. Unity is the exhibition of properties which are not inherent in the component parts of an unorganized system and which arise only when the parts are grouped in a functional aggregate. Thus size or direction are properties of a figure which must be distinguished as a unit, if the properties are recognized. With this definition it is quite legitimate to apply the concept of figure-ground relations to the animal's visual field, when a reaction is found to a property which can be derived only from a total aggregate of elements in the stimulus.[14]

This passage complicates the irreducible status of 'ground' in figure-ground relations and offers a definition of *unity* in perception, and in doing so, offers a notion of perceptual organization on the basis of biological organization. The stimulus is an aggregate, and the clean partitioning of the world of the visual field into the incoherent and coherent, is questioned. In McCulloch's and Pfeiffer's "Of Digital Computers Called Brains," the question of unity is existential – it is about about whether, when a pupil shrinks in response to light, or when other reflexes are triggered, a human being is ever truly capable of co-mingling with a world that he or she responds to.

In the electrical model of the brain, there are roles for the shreds of the neuron's anatomy: the cell membrane is understood as a leaky capacitor, the neuron's unspecified exterior is an electrical sink for the dissipation of charge.[15] I am arguing that this is the origin of the brain-computer analogy in the medical community — and yet, the basis for the comparison is not the digital computing machines of the late 1940s ENIAC-the electronic numerical integrator at the Ballistics Research Laboratory, the differential Analyzer at MIT. The analogy rests on the laws of physics — and more, the natural processes that appear to us as automated — water gushing down Niagara falls in perpetuity, a smoke ring whose consistency of form relies on an ability to turn itself inside-out. McCulloch's work is an analysis of the physical laws at work in thinking, the obedience of the body in response to what physics, as natural law, requires for thought to take place. I am arguing that biological life is understood in McCulloch's brain-computer analogy in descriptions of perception, specifically perception of a Janus-faced world that enacts both belonging and estrangement. McCulloch and Pfeiffer's world is rendered impressible by our neurophysiological witnessing of our action upon it, an impressibility made significant by its conformity with the laws of physics, laws that the world and the body *share*. McCulloch and Pfeiffer's reflection on perception and physics in "Of Digital Computers Called Brains" puts into

---

[14] Karl S. Lashley, "The Mechanism of Vision: XV. Preliminary Studies of the Rat's Capacity for Detail Vision," *The Journal of General Psychology* 18:1 (1938): 124.

[15] "For electrical purposes the cell membrane may be regarded as a leaky capacitor kept locally charged by the metabolic battery. … It can be stimulated anywhere by driving its outside negative, thereby starting a current which flows from near-by positive parts of its surface, into the excited region, partly recharging that region, but also draining the region whence it came, until it becomes a sink for current from the surface beyond it." McCulloch and Pfeiffer, "Of Digital Computers Called Brains," 370.

question *how* the world can be sensed, in the form of the degree to which the world is separate from or envelops humans and their lives.

III. The concept of Implication in The General Theory of Digital Computing Machines

The General Theory of Digital Computing, in which the nervous impulse is transformed into a mathematical function, relies on the concept of the ultimate unit in communications technology. McCulloch estimates: in the same way that Mendelian genetics resolved the problem of inheritance through quantizing the problem of inheritance using the gene, so communication technology might resolve the problems of (1) the working of the brain[16] and (2) the design of computing machines by quantizing the function of the brain and the function of computing machines using the *signal*. The signal is understood as the ultimate unit of communications technology[17] as well as the measurable basis of all cybernetics, which McCulloch terms the "science of signals."[18] "A Logical Calculus" mathematically describes how sets of neurons, *nervous nets*, deliver a signal through an open circuit on the basis of inverse feedback.[19] Returning to the electrical model offered in "Of Digital Computers Called Brains," a unit of information is defined in the terms of an impulse-signal. A unit of information is defined as "the *decision* as to whether in a given synaptic relay in a given neuron does or does not transmit an impulse"[20] will be conveyed by electrical all-or-none impulses sent by neurons as signals. The cell membrane is imagined as a capacitor, charged by a battery, the pulse travels at a rate determined by resistance, capacity, voltage, and the General Theory of Digital Computing[21] machines assumes a digital signal. The information contained in the signal is either the order in which quantities of a specific range of values occur or the number of such quantities. One of the examples offered of a digital signal in "Of Digital Computers Called Brains" is the pulse of the Morse Code, where the telegram consists of quantities of two values, a dot or dash.

> The message is the order or number of these possible quantities as in the case of dots and dashes of telegraphy and the coin of the realm. In the simplest case, this reduces to

---

[16] "Recently, the notion of ultimate units has been applied to the communications field and has opened the way to important advances in the design of calculating machines and to a better under- standing of the working of our brains." Ibid., 368.

[17] "All communication is a matter of information conveyed by signals, and the next great step was atomic signals." Ibid.

[18] Ibid., 369.

[19] "Finally, there are our appetitive circuits which, in the engineer's phrase, are inverse over their targets. It is by means of these that we have and seek our ends in the external world. In short, it is the program of the branch of the science of signals called cybernetics to analyze all purposive behavior in terms of inverse feedback." Ibid., 373.

[20] My emphasis. Ibid., 375. In relation to Wiener they write: "Following Wiener, we will define a unit of in such a circuit an enormous number of the information as the decision as to whether in a given synaptic delay a given neuron does or does not transmit an impulse." (Ibid.)

[21] Ibid., 371.

> the presence or absence – call it one or zero – of something at an appointed place or time. This is the famous binary digit now nicknamed "bit."[22]

The quantization of neurological activity in the form of the signal makes possible the discussion of a logical machine[23] where the bit – the 0 or 1 – comes to stand in for the truth or falsehood of a proposition. In McCulloch's system, the logical machine is equivalent to a digital machine[24], and the all-or-none quality of the nervous impulse makes possible the mathematical description of all nervous activity "by treating the impulse of a neuron as a proposition embodied in the signal of a particular neuron at a particular time" – by apprehending the firing or not of a the neuron's impulse as two discrete classes, the true and the false. And so the firing of a neuron is approximated in the terms of an event, in the terms of time and space, in the terms of how a signal relates to what is *happening or not*. McCulloch compares the field of physics — "in the world of physics, things either happen or they do not,"[25] to the field of communication, where there is only the signal which accurately or inaccurately communicates an external world. But the signal's relation to reality is asymmetric – like a telephone ringing with no one calling, like a finger's pressure creating an image on a closed eye:

> If you press on your eye, you will see a light when there is no light, just as when lightning strikes the wires your telephone may ring although no one is calling. In such a case, what was apparently implied had not happened, and this is the asymmetrical nature of the relation of implication, that the true only implies the true, but the false may imply either.[26]

These examples – the light and the ringing – introduce McCulloch's concept of implication. Implication is the physiological process in which a signal communicates the presence of something in the world, whether what is communicated is true (presence of light) or false (absence of light). Implication is also a logical process. In reference to the General Theory of Digital Computing, McCulloch discusses what it means for the mathematical rendering of the transmission of the nervous impulse within a net of neurons to be logical as a function of time – f(t): "In such a net, the logical relation of implication of implication extends backwards in time and backward toward our sense organs, so that what happens in our heads implies the world that did impinge upon our sense organs."[27] *That did impinge*… the world is not only discussed in

---

[22] Ibid., 368.

[23] "In fact, it was Boole's discovery of this property that led him to the attempts to construct a logical machine." Ibid., 369.

[24] In the text, the connection occurs via a citation of *Principia Mathematica*: "meanwhile, largely through the work of Whitehead and Russell, much of mathematics has been reduced to logic. Thus, today one speaks of any de- vice for communication which performs its computations by these discrete signals indifferently as either a digital or a logical machine. And all large modern computing machines are principally digital." Ibid., 369.

[25] Ibid., 371.

[26] Ibid.

[27] Ibid.

terms of impingement of our sense organs in reflex servomechanisms.[28] The world is discussed in terms of our ability to adjust to it: "The impulses descending from our heads play upon complicated servomechanisms that keep us adjusted to the world about us in motion and at rest."[29] The organizing concepts of the relationship between the brain-digital machine and the world, which are the stakes of implication, are: (1) time (2) inverse feedback of which the device,[30] the reflex, is the consummate example and (3) perception – perception because the organ most often discussed besides the brain is the eye. McCulloch and Pfeiffer's analysis of an eye's ability to see constitutes their second discussion of the eye and implication. There is a true signal, *light*, that in the anatomical communication of retina to brain implies the *true, implies the presence of light:*

> In the case of vision, three such devices work one after the other. First the slow adaptation of the retina to light; second, the quicker pupillary reflex, and third the automatic volume control of impulses relayed to the cortex — rid a form to be seen of its variable intensity at the input, so that we know that there was some brightness of illumination, which was of the given figure. Because these devices generally pull toward one value predetermined for us in the scheme of our nervous activity, the final value seems to us, God-given, and the process is said to reduce the input to a canonical brightness or what-not.[31]

The reflexes described are three: (1) general adaptation of the eye to light (2) the pupillary reflex, which changes the circumference of the pupil in the presence of light[32] (3) reduction of the variable intensity[33] of the stimulus so that the mind can correctly perceive the degree of brightness present in the environment. The goal of each of these three, working one after the other, is to alter the intensity of the initial input, mid-circuit, so to achieve a pre-determined value for that intensity — and the end of their actions? "So that we *know* there was some brightness…." What is purported is some threshold value of intensity for each, perceptible degree of brightness, where an intensity at a certain level corresponds to our knowing that there is present, a dimness, a blindness, or a light.

---

[28] "Many of them (reflex paths) are, in fact, servomechanisms, for we can by impulses imminent on neurons in the path of a given reflex determine the particular value of the variable sought by that reflex." Ibid., 373.

[29] Ibid., 371.

[30] In relation to the reflex: "In the case of vision, three such devices work one after the other." Ibid., 373.

[31] Ibid.

[32] See A. P. Belliveau, A. N. Somani, and R. H. Dossani, "Pupillary Light Reflex, " *StatPearls*. (Treasure Island, FL: StatPearls Publishing; 2020). Updated Jul 31 2020. <https://www.ncbi.nlm.nih.gov/books/NBK537180/>. Accessed Dec 8 2020. They write: "Eyes allow for visualization of the world by receiving and processing light stimuli. The pupillary light reflex constricts the pupil in response to light, and pupillary constriction is achieved through the innervation of the iris sphincter muscle."

[33] "[S]econd, the quicker pupillary reflex, and third the automatic volume control of impulses relayed to the cortex — rid a form to be seen of its variable intensity at the input, so that we know that there was some brightness of illumination, which was of the given figure." McCulloch and Pfeiffer. "Of Digital Computers Called Brains," 373.

IV. Time and voltage as value and norm

In "Of Digital Computers Called Brains," the mathematical model of the transmission of the neural impulse submitted in "A Logical Calculus" is named "The General Theory of Digital Computing," and in this theory the independent variable is *time*. The notation of the function is *f(t)*. With reference to the General Theory, McCulloch & Pfeiffer offer the following:

> The calculus is very simple. It is made from the calculus of atomic propositions of Whitehead and Russell, by treating the impulse of a neuron as a proposition embodied in the signal of a particular neuron at a particular time-and that time is measured in synaptic delays. For example, N7 (t-3) means that neuron number seven transmitted an impulse three synaptic delays before an arbitrary origin of time.[34]

Time in the formal model of nervous activity is measured in units of synaptic delays. A synaptic delay is the time required for the nervous impulse to be transmitted across a synapse, the junction between two neurons,"between the axon of one neuron and the soma of another"[35] – the axon is the tissue that stretches from the soma, the site of the neural cell's nucleus, to the terminal endings of neuron. As to why the focus is breach, the fluid intervening between cells, McCulloch and Pitts offer this: "The time for axonal conduction is consequently of little importance in determining the time of arrival of impulses at points unequally remote from the same source." In the calculus, the parameters, time, establishes an identity relationship between the activity of neurons of the central nervous system and the activity of relays in digital computing machines. The value, time, is shared by the machine and the brain, modeled by the same formula. In the calculus, "the nervous system is a net of neurons," and the value that determines how the signal is communicated accrues in the distance between neurons as the time required for the transmission across the synapse.[36] There are two forms of value present in the calculus; first, the electrical catching up of charge (the digital signal transmitted in both systems is contingent upon the system's components achieving a certain value for the following variable: number of impulses[37]), and second, time.

Working during the same period, George Canguilhem, in *The Normal and the Pathological*, also considers value in the context of physiology. The *Normal and the*

---

[34] Ibid., 371.

[35] McCulloch and Pitts, "A Logical Calculus," 343.

[36] Ibid.

[37] Between the arrival of impulses upon a neuron and its own propagated impulse there is a synaptic delay of > 0.5 ms. During the first part of the nervous impulse the neuron is absolutely refractory to any stimulation. Thereafter its excitability returns rapidly, in some cases reaching a value above normal from which it sinks again to a subnormal value, whence it returns slowly to normal." (344). Ibid. And furthermore: "No case is known in which excitation through a single synapse has elicited a nervous impulse in any neuron, whereas any neuron may be excited by impulses arriving at a sufficient number of neighboring synapses within the period of latent addition, which lasts ~0.25 ms." Ibid., 343.

Pathological (which was first published in 1943, then expanded in a later edition) reconsiders the machine-animal analogy taken up in the 1948 lecture, “Machine and Organism.” He writes:

> In short, to consider the average values of human physiological constants as the expression of vital collective norms would only amount to saying that the human race, in inventing kinds of life, invents physiological behaviors at the same time. But are the kinds of life not imposed?[38]

Human physiological constants can be understood as those numerical values corresponding to measurements of the organism deemed livable, such as visual acuity, blood pressure, and glucose levels. *But are the kinds of life not imposed?* Canguilhem questions whether the kinds of life invented by the organism are true inventions: whether they are *chosen* or whether they are instantiated on the basis of necessity in response to an organism’s environment. Canguilhem, in reference to Kayser, uses the example of the homeothermic animal’s circadian temperature rhythm and electric light to argue that the values of the organism,“norms of life”[39], are always in relation to technology and meted out in confrontations with the environment:

> Here, then is an example of a constant related to the conditions of activity, to a collective and even individual kind of life, whose relativity expresses norms of human behavior in terms of a reflex conditioned to variable disengagement. Human will and human technology can turn night into day not only in the environment where human activity unfolds, but also in the organism itself whose activity confronts the environment.[40]

Here, the inner values of the organism are modulated in reference to an environment that is also modulated, changed by human will and human technology, and the reflex is understood in the terms of conditional withdrawal – and I argue, perception – rather than in the terms of the automatic or embedded.

McCulloch and Pfeiffer note how signals imply a world — and only the world in some *past state* and not in a future state: “Notice also that the domain of this implication of signals extends only into the past. What is going on our heads at a given relay time does not imply what is yet to happen in our arms and legs.” McCulloch and Pfeiffer’s *implication* occurs in time and requires a past, as the incarnation of a logical process. *Implication* is the physical enactment of the logical and mathematical proposition, the calculus. Mark that this is also a commentary on free will. *The response to the stimulus* is undetermined. What will take place in “our arms and legs” can be caused by a stimulus impinging upon the sense organs as there are certain reflex loops that are unregulated by intention: “These have their own feedback over afferent, peripheral neurons, and the impulses coming by these shorter paths may so determine their behavior that something else may happen instead of what we intend.”[41] The reflexes of body temperature,

---

[38] Georges Canguilhem, *The Normal and the Pathological,* tr, Carolyn Fawcett (New York: Zone Books, 1989), 176.

[39] “But from the moment, several collective norms of life are possible in a given milieu, the one adopted, who's antiquity makes it seem natural, in the finally analysis, *the one chosen*.” Ibid.

[40] Ibid., 177.

[41] 371. McCulloch and Pfeiffer. “Of Digital Computers Called Brains,” 371.

blood volume and the ability to stand at sea – are understood in McCulloch's work as facilitated by a circuit, whose fluctuations in the number of impulses induce a corrective response by the components of that circuit, to return to the circuit to a pre-established state.[42] As McCulloch and Pfeiffer explain:

> So much for the regenerative closed paths of memory. All other paths are normally inverse — that is, they work on the general principle of the governor of a steam engine. When the engine is running faster or slower than a certain level, the governor senses the discrepancy and more steam is fed into the boiler or released from it. Similarly,….each inverse path of the brain establishes some state or level for its system, by bringing the system back toward that state whenever there is a displacement in any direction. The established state is the end in and of the operation of its system. This is the fundamental nature of the function.[43]

The description of the nervous system's adjustments is only ambivalently set in the terms of automation — for a conductor of a steam engine, a figure of human agency and control, is the one capable of noticing a discrepancy in the volume of steam in the boiler, in search of a pre-determined value for the variable, steam. Is McCulloch rendering a servomechanism teleological, here? The function is in possession of a fundamental nature, and electrically, the function is in possession of a variable (current, voltage) which achieves a certain value in order for the reflex to be enacted, the signal to be sent and the body to respond. In the midst of an extended comparison of the nervous system to digital computing machines, we have a man, an analog machine (steam engine) whose work is apprehensible through dimensional analysis[44], and *steam,* whose physicality is almost domestic, quotidian. In a similar reflection on force and matter McCulloch discusses what it would mean to build a digital machine that has 10^10 neurons, as many neurons as can be found in a human brain.[45] "A computer with as many vacuum tubes as a man has neurons in his head would require the Pentagon to house it, Niagara's power to run it, and Niagara's water to cool it."[46] To make an electrical model of the brain operational would require nature as an energetic upper and lower bound. The power (energy per unit time) of Niagara Falls is required to operate the 10^10 vacuum tubes of the electrical model of the brain and the heat capacity and material availability of Niagara Falls' water, acting as a coolant, is required to reduce the heat generated by the vacuum tubes. Other than furnishing the physical space needed to shelter the electrical model of the brain, Nature is self-sufficient, operating in

---

[42] For examples, see ibid., 373.

[43] Ibid., 373-374.

[44] See the somewhat peculiar discussion of dimensional analysis and disease at the conclusion of the paper: "Every time we build an inverse feedback into a ma- chine we make it possible for it to have a comparable gremlin, and gremlins are diseases which defy dimensional analysis." Ibid., 376.

[45] "As a device for handling signals, the brain can be conceived as an ensemble of nerve cells or neurons, which act quasi-independently. There are some 10^10 of them, and they constitute about a twentieth of the total volume of the central nervous system." Ibid., 369.

[46] Ibid., 370.

two directions. Nature provides the resources to generate the energy that sustains nervous activity and to dissipate the energy. Nature exemplifies work in two directions, allowing for nervous activity's continuation, and Nature is a conceptual recourse, making the analogy between the brain and the digital machine work because of its ability to augment man-made machine's deficits. In its limitlessness, it augments the quantities of the machine. It contributes energy and size. It allows the machine to attain values that would otherwise be those of life.

In the description of how the anatomy of the neuron makes it possible to communicate information by electrical impulses, McCulloch offers the following:

> … it [the neuron] can be stimulated anywhere by driving its outside negative, thereby starting a current which flows form near-by positive parts of its surface into the excited region, partly recharging the region, but also draining the region whence it came until it becomes a sink for current form the surface beyond it.[47]

This is an approximation of the depolarization of the neural cell's membrane and the accrual of positive charge within the cell that characterizes the the transmission of an action potential down the length of the axon. "The pulse of current travels along the neuron" McCulloch writes, "turning itself inside out like a smoke ring."[48] The reversal of the membrane potential, the churn and exchange of positive charge with negative charge, is described as the movement of smoke particles from the interior to exterior of a vortex ring, where the outward movement maintains the ring's very form.[49] What is automatic in nature that possesses similarity to the automaticity in digital computing machines? What does a discussion of automaticity in terms of the earth, in terms of physical material of smoke and water mean for McCulloch's argument about the inverse feedback of the human reflex? I argue that any automaticity attributed to nature in McCulloch and Pfeiffer's text has its basis in the perception of natural processes occurring consistently according to natural law. If the digital machine were in fact a figment of organicism, an *organic* machine, it would mean that human life is somehow apprehended by natural law, the same natural law that gives force and movement to inanimate objects – a smoke ring, the interminable rush of Niagara's water.

---

[47] Ibid., 370.

[48] Ibid.

[49] "A vortex ring usually tends to move in a direction that is perpendicular to the plane of the ring and such that the inner edge of the ring moves faster forward than the outer edge." "Smoke Rings – Air Vortex Movements," Science in the City, Stanford University. 2020. <https://scienceinthecity.stanford.edu/resources/smoke-rings-air-vortex-movements/ >. Accessed. Dec 8 2020.

V. Coincident circuits in the physiology of perception

McCulloch's digital machines have the possibility for the expression of will in the ability to compare what they compute to what they make available for us to read.[50] These machines have memory.[51] The behavior of these machines correspond to inverse functions, where feedback loops allow for the adjustment to an equilibrium. As mentioned, sense organs contribute information to neural feedback loops to allow for adjustment. Reflexes work in this way, relying on servomechanisms to trigger certain responses in the body. The value is predetermined, "pre-assigned": "Because each feedback circuit brings some aspect of an input back to a pre-assigned value, it rids that input of the gratuitous particularity of that value it had been when we encountered it." On the reflex as a servomechanism that possesses automaticity in the form of self-correction: "Many of them (reflexes) are, in fact, servomechanisms, for we can by impulses imminent on neurons in the path of a given reflex determine the particular value of the variable sought by that reflex." The summation of impulses, also understood as the "inputs" of a digital computing machine, determine the *value* catching up in the circuit, which permits or disallows the circuit to achieve the threshold value that would cause the reflex action to take place. The impulses, through their achievement of particular value, register a specific attenuation of the world for the brain to make sense of.[52]

Vision is the physiological and anatomical example of different servomechanisms called "devices" outside of the reflex function described by McCulloch, and such "devices" consist of anatomical means of correcting the value of an input, ridding an electrical response from its particularity,[53] so that the system can return to an established value correlated to a specific bodily response. These means of anatomical correction are (1) coincident circuits (2) parallel paths and (3) neuroplasticity. These are also the mechanical corrections for information dissipated as noise in digital computing machines.[54] To mark the structure of the argument, McCulloch moves from the machine to the body – it is not always this way, but discussion of the physiological error of an incomplete circuit begins with how machines lose control over information.

The machine's porousness is understood in terms of entropy increasing constantly within the system information moves through. And information? Information is understood as the opposite of entropy, possessing a negative value for the mathematical metric for understanding entropy:

---

[50] "This causes us to distinguish between what we will and what we shall do and, in forcing this distinction, has created the notion of the will. When we build computing machines that can compare what they intend with the record they make for us to read, they will become confronted with a similar difficulty, and may then be said to have wills of their own." Ibid., 370.

[51] "Modern computing machines have several kinds of memory." Ibid., 371.

[52] Ibid., 373.

[53] Ibid.

[54] "The second law of thermodynamics, which insures an increase of entropy, means that information can never increase as it passes through any computing machine." Ibid., 375.

> For each unit of information subtract 1 from the exponent. From this it follows that the amount of information in an ensemble of neurons is the logarithm to the base two of the reciprocal of the probability of the state, which is called entropy. Thus, information is negative entropy. The second law of thermodynamics, which insures an increase of entropy means that information can never increase as it passes through any computing machine.[55]

I will now address the philosophical consequences of the answer to McCulloch's question *how can we get adjusted to the world even given defective paths?* It is necessary to turn to the eye as the organ from which to derive an understanding of the circuit action of nervous activity. In the case of the eye, the problem is presented in the terms of how much information is *received* by the organ capable of recognizing what the value of the system *means*.

When McCulloch writes about the eye, he writes about (1) brightness and (2) form. Below is McCulloch's account of the first means of correction: (1) coincidence. Coincidence can be understood as an anatomical requirement that many similarly stimulated nets converge at the point of destination, where the value achieves a certain threshold for the brain's recognition.

> Impulses from the hundred million photoreceptors of each eye converge through bipolar cells on, say, a million ganglion cells whose axones extend into the brain. The thresholds of these transmitters to the brain are sufficiently high so signals from many sources must converge on them contemporaneously to trip them. The convergence of these connections is obviously of the order of 100 to 1. The requirement of coincidence insures that the impulses that do reach the brain have a high probability of corresponding to something in the world, for the chance of error may be reduced to one part in 2^100, or about one part in 10^30.[56]

The requirement of coincidence insures that the impulses have a higher probability of corresponding to something in the world - this is the achievement of the reduction of error. The stakes are those of recognizing a world one can respond to. This is to mark the stakes of the anatomical correction for error: (1) coincidence, (2) parallel paths, and (3) neuroplasticity. The corrections do not merely ensure that the proper value for voltage accumulates at a specific site in the nervous system at a particular point in time, they ensure a correct *response*. The corrections ensure a unity with the earth and an obedience to natural law that the neuron structurally facilitates. How McCulloch understands the innervation of the body – as neurons, grouped as circuits – as relay components, within a matrix of relay components – is also an anatomical rendering of natural law, here understood as the quantization of matter – "we live not in an atomic world in the sense of the chemist, but in the particularized world of the nucleonic physicist – a world ultimately composed of a very large number of a very few kinds of particles, with even their energies and possible positions atomized."[57] This is a world in which

---

[55] Ibid.

[56] Ibid., 375.

[57] Ibid., 368.

continuities are but *apparent continuities* and best comprehended as "some number of some little steps." To quantize the central nervous in terms of its signals is but a shorthand for quantizing the nervous system in terms of its particles: "The whole development of the anatomy and physiology of the nervous system suggests that we can simplify the problem."[58]

> The human brain consists of, say, 10^27 or 10^28 of the ultimate particles of the physicist, and one might describe how it works by stating how those particles behave-and we may ultimately be able to do so. But for our purposes it would be about as silly as to describe a chair by the motions of its component particles…As a device for handling signals, the brain can be conceived as an ensemble of nerve cells or neurons, which act quasi-independently.[59]

Independent neurons which transmit the nervous impulse on an all-or-none basis is a scaled response to the question of quantization: the argument is that the brain's activity could be understood on the basis of each individual particle that composes the matter of the brain, but the current state of science, "knowledge of all descriptive details,"[60] fails to grasp the activity of each individual particle.

The mechanism by which coincidence functions in the physiological function of perception is as follows:

> The anatomy of one of the most interesting of these reflex circuits was described by Cajal, and its physiology was discovered by Julia Apter. It goes from the eye, whose field it maps on the back of the mid-brain in the superior colliculi, structures which compute a vector from the center of the line of gaze to the center of gravity of the retinal excitation, and relay this vector to the oculomotor system. This system then turns the eye so as to reduce the vector to zero, bringing the apparition to the canonical position which is the center of the visual field, represented as the fovea of the eye. In this way it rids the form to be seen if the gratuitous particularity of the place where it was first detected. Now, short of going toward or from objects, there is no way to move our eyes that will reduce the image to a canonical size on the retina. But there is another way of attaining the same end. This depends, as we shall see, on a kind of averaging performed in a net whose output is not significantly altered by minor changes in the thresholds of neurons or their excitations, or even their connections so long as these be to cells in the right neighborhood. One can even poke holes through such a net and still have it work well for most purposes.[61]

---

[58] Ibid.

[59] Ibid., 369.

[60] "It has been said that since the days of Helmholtz , no man can understand all science. If by this is meant knowledge of all descriptive details, it is increasingly true. But there are many signs that at the level of theory the most remote of disciplines have developed central ideas that are pulling them (details) together." Ibid., 368.

[61] Ibid., 373.

Apter was an anatomist working at Hopkins, experimenting with nerve fibers and vision[62]. Cajal is the physician and anatomist whose cross-sectional drawings, like those of the reticular formation and frontal lobe, serve as the slides McCulloch most often made use of in papers. Coincidence is anatomically accounted for in the process of focusing an image *of appropriate size,* on the fovea of the eye. At issue is the achievement of the "canonical size" of the perceived object on the tissued surface upon which that image is projected in the retina. What changes from the moment in which the stimulus is sensed in the "place where it was first detected" to the moment in which the apparition is constructed in the fovea of the eye?

One way of altering the size of the apparition projected upon the fovea is "a kind of averaging."[63] "Gratuitous particularity" is removed from the form to be seen , which, in the present, is represented as an impulse. Time is figured here, too. Previously, in McCulloch's concept of implication, time was applied to the world as a quality – where the world was always "past" to the instant of sensation. An analysis of time as a quality of the world can also be understood from the f(t) function for the transmission of the nervous impulse within a net of neuron, where time functions as the content of a variable within a nervous net. Time is understood in terms of degree, "more" or "less" time from an initial exogenous stimulus to the firing or not of a particular neuron in question. The eye example, predicated upon a moment in which the object's image will be physiologically instantiated, makes clear how conscious reception of impulses as *image* upon the fovea happens according to some futurity, some future contingent upon the body's physiological capacity to create an image from a series of impulses. The significance of this point, that the world is past and consciousness of that world is in futurity is that the neuron perpetuates in some interminable present, apart from consciousness, apart from the world as a gossamer medium. One conceptualization of life, then, is this reverberating present that promises a conscious response and recognition of a world.

The averaging, where "particularity" is removed from the form to be seen, later represented as a logarithmic function, takes place prior to any physiological recognition of the form of the object.The group of neurons in the retinal circuit that constitute a net can *average* their values, achieving the appropriate value due to a multitude of neurons in the net – "or cells in the right neighborhood," achieving an independent value that then can be amassed and averaged. This averaging within nets is contrasted with physically moving away from or toward an object in a conceptual turn that would appear to resemble a programming problem: "Now, short of going toward or from objects, there is no way to move our eyes that will reduce the image to a canonical size on the retina." Seemingly, there is an ability to achieve a material end (diminution of the image on the fovea) by symbolic means, the mathematical averaging of signals of an all-or-none value; but the conceptual affordance is more nuanced, as the means are dually symbolic and material. The last sentence is no doubt an allusion to lobotomy: "One can even poke holes through such a net and still have it work well for most purposes," as are the final

---

[62] Julia Apter, "Projection of the retina on superior colliculus of cats," *Journal of Neurophysiology,* 8:2 (1945): 123-134.

[63] "This system then turns the eye so as to reduce the vector to zero, bringing the apparition to the canonical position which is the center of the visual field, represented as the fovea of the eye. In this way it rids the form to be seen if the gratuitous particularity of the place where it was first detected." Ibid., 373.

sentences of the paper.[64] One pokes holes in a net of neurons only through trepanation, the process in which an orbitoclast 'ice pick'[65] is used to drill through the skull to the cerebral cortex. The case study of perception renders clear the central problem of the paper: how flesh facilitates a symbolic system encompassing sensation and response. The retina, the superior colliculi, the fovea, the *image*. Perception is all then more captivating because of the questioning of materiality the process of perception requires: is *brightness* a dimensional metric? Is form? Is the image projected on the back of the fovea *material?* What does virtual mean in this context, in the context of an impulse that leads to a projection that leads to a reflex response in the form of an impulse and tightening or widening of a pupil. To be clear, the reflex analyzed in the passage above is the *turning of the eye* through the excitation of the oculomotor system that "reduce(s) the vector to zero, bringing the apparition to the canonical position which is the center of the visual field."

VI. Regenerative circuits and purposive behavior

McCulloch and Pfeiffer describe how size is presented to consciousness: an input, as a nervous impulse in response to visual stimulus, "produces a small roughly circular area of stimulation in the primary visual cortex", and depending on which layer of the cortex the impulse terminates in as a circular area of stimulation, a specific height will be attributed to the perceived object: "circles on the cortex correspond to ovals in the visual field, having the small ends of their long axes pointing at the point of fixation."[66] The fact of many layers means that the image can be of many different sizes. Remember that the discussion of central nervous system's role in vision begins from a discussion of inverse paths: "each inverse path of the Brian establish some state or level for its system, by bringing the system back toward that state whenever there is a displacement in any direction."[67] The circuits that McCulloch perceives as functioning in the central nervous system are of two kinds (1) inverse feedback (2) regenerative. The archetype of the inverse feedback circuit is the reflex, and the regenerative loops are the basis of both

---

[64] "We know something of the whereabouts of these vicious regenerating circuits in two or three mental conditions. In the early states, we may stop the process by blocking the regenerative loop or, by sufficiently violent excitation over other channels, steal from it those neurons it had swept in phase and so reduce its gain to the point where it ceases to regenerate. But later it becomes necessary to section the paths. When this can be done in peripheral nerves or in the spinal cord, the patient suffers minor mayhem. But when we have to cut the loops uniting the forefront of the brain with deep structures , we destroy some of the highest traits of character — certain judgments with respect to things and men, and the ability to discovery new underlying generalities among ideas." Ibid., 375.

[65] See discussion of the ice pick method, see Jack Pressman, *The Last Resort: Psychosurgery and the History of Medicine* (Cambridge: Cambridge University Press, 2002), 322, 342.

[66] McCulloch and Pfeiffer. "Of Digital Computers Called Brains," 373.

[67] Ibid., 372.

memory[68] and neuropathology[69]. McCulloch's conception of the regenerative circuit is contingent upon the work of Lawrence Kubie, who understood regeneration as a pathological intensification, the regenerative circuit increase its gains "until it overloads itself maximally," until it is rendered useless in its inability to internally communicate information related to the external surround.[70] What the circuit becomes overloaded with is charge, voltage and more secretly, the threat of being severed from the world:

> When a circuit of this kind becomes regenerative, the regeneration tends to grow until the circuit has swept into its orbit all the cells that it can force to fire in phase…It now ceases to transmit any information. Such was the howling of our old one-tube receivers, with a feedback from the plate to the grid when the gain was too great. When such a circuit action persists long enough, it causes some sort of change in us such as that underlying the acquisition of skilled acts. We may then turn off the circuit temporarily, and, when we turn it on again, it will get going in its old regeneration. In fact, any input that can contribute, however indirectly, to its excitation will start howling as before.[71]

Note how McCulloch and Pfeiffer's argument is structured. *Such was the howling…* where the incapacitation of a one-tube relay component, a tube for the transmission of charge, is a process that mimics the incapacitation of neurons in nets that have lost control over the ability to distribute and regulate charge in a physiological system. Fundamentally, this process affects behavior, which is why McCulloch discusses the change induced at the level of the whole organism, in which the ability to acquire skilled acts is diminished.

Behavior is predicated upon an idea of world-building, where the automaticity promised by the reflex servomechanisms, which, in the manner of automatic volume control built into a radio, correctly control for the values of the system, also preserve a relationship to the external world. This relationality demonstrated by the reflexes could be considered one conception of life, a metabolic relationship to the external world, one not rooted in an idea of material consumption but rather in an idea of *responsiveness*. What is metabolized is a set of stimuli, translated into electrical signaling, which, in their anatomical containers, represent a world that the body is materially capable of changing. Freighted with the opportunity to build and respond to a world, the appetitive circuits are discussed in reference to the science of cybernetics as a whole:

> Finally there are our appetitive circuits which, in the engineer's phrase, are inverse over their targets. It is by mean of these that we have and seek our ends in the external world.

---

[68] "This can only be accounted for by some regenerative process capable of multiplying traces before they fade, and only be accounted for by some regenerative process capable of multiplying traces before they face, and only protein molecules - nucleoproteins, to be specific - seem to possess the ability to generate others templates after themselves." Ibid.

[69] "We know something of the whereabouts of these vicious regenerating circuits in two or three mental conditions." Ibid., 374.

[70] Ibid., 375.

[71] Ibid., 375.

> In short, it is the program of the branch of the science of signals called cybernetics to analyze all purposive behavior in terms of inverse feedback.[72]

Purposiveness in this system will always be firstly understood in the physiological interior, the return of voltage to a constant, established level. And yet, here there is a suggestion of *a teleology apart from the return of the voltage to a steady state*. Here the appetitive circuits, most immediately understood as the biological requirements of metabolism (glucose, oxygen, water; hunger, breathing, thirst) are apprehended as the means by which we seek the external fulfillment of an internal teleological requirement. Physiologically, this becomes: *how do we perceive the world we build, the norms we institute, to stay alive?* To McCulloch and Pfeiffer, this second purposiveness, the purpose of seeing what one effects in then world, is the question that cybernetics is charged with answering.

What remains to be analyzed, then, is the (1) form and (2) brightness of perceived objects. How is the physiological production of the size of the image different from the physiological production of the shape of the image in McCulloch and Pfeiffer's text?

> At the present moment, it seems possible that the so-called alpha rhythm of the brain is the sweep of the alerting pulse through the cortex, for its frequency (about 10 per second) is that at which one can see shapes regardless of size or hear chords regardless of pitch. If this be the answer, then the alpha rhythm should disappear — as it does — when the cortex goes to work with attention to its input as in looking at anything, for the signals in its receptive layers and in its large output neurons have their principal voltage gradients also directed, vertically through the cortex of a man awake with his brain exposed at operation should produce - as it does— an apparent ovoid blob of light, whereas stimulation of the secondary visual cortex should give us, as it does a form seen.[73]

The frequency of alpha waves is 10 impulses per second. The rate, 10 impulses per second, is an anatomical summary, a depiction of the entire cortex in a given state, "the sweep of the alerting pulse through the cortex," understood as a frequency. This frequency is significant because it is described as that which makes possible the discernment function in perception, the ability to "see shapes regardless of size" and the discernment function in hearing, "hear chords regardless of pitch." Frequency somehow includes a subtle awareness of the presence of an object to be made sense of, a subtle awareness of being accompanied.[74]

VII. Responsiveness in time and space

Much resides in the mystery of the simultaneity of stimulus and response. The electrical, digital signal in its rushing through the body is bi-directional, not just 0 and 1 but, *afferent and efferent,*

---

[72] Ibid., 373.

[73] Ibid., 374.

[74] Ibid. They also write: "At the preens moment it seems possible that the so-called alpha rhythm of the brain is the sweep of the alerting pulse through the cortex, for its frequency (about ten per second) is that at which one can see shapes regardless of size or hear chords regardless of pitch." Ibid.

inwards and outwards. There is a formal isomorphism at the level of the electrical, digital signal: that is, the signal that communicates a dimensional world is materially identical to a signal that carries the body's response to that world, a response that not only portends a 'co-mingling' in the manner of one's own dimensionality joining with, say, a light coming on in a room[75], but also portends the ability to alter that dimensional world. This potential for changing the external reality is the key component of the understanding of life as a particular relationship between the subcutaneous and the external world.

The *responsiveness* that automaticity promises does not merely speak to a liveliness in the body in the ability to *be stimulated*, to *be moved*, to *be induced* , but to the response that takes a dimensional form, which in turn becomes part of the world an instant after it was first metabolized. Time, as one of the values, is here understood as a distance. Where nets, as groups of neurons are capable of "exchanging time for space" through the ability to either (1) have one neuron send multiple impulses in a given amount of time (2) have multiple neurons transmitting an impulse at once concentrated upon a particular site in the brain - as previously seen in the ocular example, where the magnification is discerned on the basis of amount a stimulus applied in a certain layer of a mosaic of neurons.

> Moreover, a net of neurons can convert any figure of simultaneous signals over a given number of neurons into a sequential figure of impulses over one neuron, occupying as many synaptic delays as its prototype required neurons simultaneously, thus exchanging space for time. Conversely, it may exchange time for space.[76]

A net can mimic a web of neurons delivering an impulse through one neuron, thus agglomerating impulses in one location delivered in one second, vs. impulses arriving from various locations. The mathematical understanding of this concept is represented in what follows, in the approximation of the Logical Calculus, as the theory of coding devices. (Figure 2)

---

[75] In the eye example, what is considered 'true' is the correct understanding of what took place in the world (light shining onto sense organ) before the nervous system's communication of that taking place.

[76] Ibid., 374.

III

We may characterize all processes of this kind as follows. Given an input, we may lead it into a matrix of relays and there make all the transformations belonging to some group—in the visual example, magnifications and dimunitions. Then we compute a set of numbers, q, each of which is the average—for all transformations of the group $(T \varepsilon G)$ of the value assigned by some arbitrary functional, f, to each transformation (T) as a figure (ϕ) of excitation in time, t, and space, x, in our matrix. This gives us the following expression:

$$q = \sum_{T \varepsilon G} f\,(T(\phi\, x\, t)).$$

Figure 2.

Image of the matrix representation of values.
From McCulloch and Pfeiffer, “Of Digital Computers Called Brains”

Upon the averaging of the mathematical representations of the eye's work on size (how the neural nets reflect diminution and magnification, upon an averaging of these) a function emerges, where the activity of the neuron can be represented as a function of time and space – *a figure of excitation in time and space in the matrix* – and this, in an example from the eye, is the mathematical consistency that McCulloch ascribes to a set of neurons.

What differentiates a representation of the world from a representation of an action that will change that world is *time* – f(t). The electrical current understood in the terms of the binary bit serves as the basis of McCulloch's research as what designates his work as belonging to the field of cybernetics. The current that is in machines and bodies, is *transposable* and *undetermined*, whether it is coming from a world or seeking a world.

VIII. Error and the perceptual information of the brain opened on the operating table

Wilder Penfield, author of the textbook *Cytology and Cellular Pathology of the Nervous System* (1932)*,* was a neurologist and neurosurgeon practicing at McGill University and the Montreal Neurological Institute from 1931-1960. Penfield devised a method of electrically stimulating the cortex of patients under anesthesia to "map the cortex"[77] – to stimulate the brain and then cause "somatic sensations located to a specific part of the body." Called the "Montreal Procedure," Penfield's landmark operation would include a patient who is operated on *while awake* and *without pain* due the fact that "the brain tissue itself lacks the receptors of somatic sensation."[78]

For McCulloch and Pfeiffer, the evidence provided for the localization of different neural functions, where the primary visual cortex is the region responsible for perceiving the *size* of the object, and the secondary visual cortex (picture) is responsible for perceiving the object's *shape* – this is what is *seen* by a *patient* on a Penfield operating table when a stimulus is applied to a certain area of the brain. Upon the application of current to the secondary cortex instead of the primary cortex, the patient is able to perceive form where previously there was only an "ovoid blob of light." The release from formlessness takes place upon the cortex being stimulated in certain areas while the patient is "awake with his brain exposed at operation." Life, perceptual life, is indebted to electricity, where the application of electrical force to the secondary visual cortex results in the ability to give form to objects in a sensate world.
Electricity is tied to life again, when McCulloch is writing about the regenerative circuits that identify such neuropathologies as neurosis: "We must, while they [neurons] are alive and active, detect electrically what portions are regenerating." Here, electricity furnishes a tool for

[77] See Mark F. Bears et al., *Neuroscience: Exploring the Brain,* 4th ed. (Philadelphia: Wolters Kluwer, 2016): "Electrical stimulation of the S1 surface can cause somatic sensations localized to a specific part of the body. Systematically moving the stimulator around S1 will cause the sensation to move across the body. Canadian neurosurgeon Wilder Penfield, working at McGill University from the 1930s through the 1950s, actually used this method to map the cortex of neurosurgical patients. (It is interesting to note that these brain operations can be performed in awake patients, with only local anesthesia of the scalp, because the brain tissue itself lacks the receptors of somatic sensation.)" (431)

[78] McCulloch and Pfeiffer. "Of Digital Computers Called Brains," 375.

understanding life - the diseased neuron must be assessed *electrically*[79] *before they die*. For McCulloch, diseased, moribund neurons and living, healthy neurons exist along a continuum - the same continuum that exists between inverse circuits and the regenerative circuits, where the regenerative circuits themselves can contribute to either (1) functions of memory or (2) neural degeneration as in the case of neurosis or Korsakoff's syndrome (here referred to as Korsakow's syndrome). The precipitous scene of neurosurgery is ever more poignant, ever more revelatory in relation to the idea that what is lost in neuropathology is only the loss of information.

Earlier, coincident circuits were described as one of three ways McCulloch identifies for how the anatomy of the brain rectifies neurophysiological error in the form of a myriad of neurons converging at one point (through bipolar cells[80]) to ensure the proper number of impulses in a given period of time. The sense McCulloch refers to in the discussion of coincident circuits is *vision*, so the delivery of the proper number of impulses will ensure the sight of what first stimulated the brain's hundred million photoreceptors.

> Since each human eye has a hundred million photoreceptors, each capable of transmitting once unit of information per synaptic delay, a man receives at least 2X10^8 units of information per millisecond. It is possible to estimate the information he puts out per millisecond by noting that a new telephonic device, sampling speech once per millisecond and emitting one pip or none according to the instantaneous amplitude of the sound wave, transmits almost all the information converted by the Human voice. So the amount of corruption in a single passage of information through a man is about 10^8.[81]

It is the discussion of *error* that necessitates a comparison of the brain with computing machines, the discussion of *failure*. The physical register for ascertaining the rate of transmission of impulses not lost to noise - "Actually, we know that information is always corrupted in every device for communication. It is only noise that increases" in the telephonic device, a communications technology device designed for transforming what the ear might hear into pips: "emitting one pip or none according to the instantaneous amplitude of the sound wave."[82]

The machine McCulloch refers to is also referred to in "The Biological Sciences" (1966), in terms of the advent of information theory. McCulloch and Brodey explain: "When information theory began about 1927 at the Bell Telephone Laboratories, the problem was how much information is conveyed by human speech turned into electrical signals on a wire and understood by a human listener."[83] To discuss total stimuli reception in the terms of the vision of the man, "2 X 10^8 units of information per millisecond"[84] and to discuss total information transmitted through the nervous system in terms two, layered processes (1) "the information he (the man)

---

[79] "…while they are alive and active…" Ibid., 376.

[80] Ibid., 375.

[81] Ibid.

[82] Ibid.

[83] Warren McCulloch and Warren Brodey. "The Biological Sciences," in Robert Hutchins and Mortimer Adler, eds., *The Great Ideas Today, 1966* (Chicago: Encyclopedia Brittanica Inc, 1966), 295.

[84] McCulloch and Pfeiffer. "Of Digital Computers Called Brains," 375.

puts out" as stimuli for the device and (2) the total information transmitted processed by the device, which "transmits almost all the information converted by the Human voice", is not only to establish a primary relationship between the senses of vision and hearing, it is to, in a series of translations, establish the device as the cortex in a discussion of corruption in the human nervous system.[85] Based on the series of transmissions, electric and auditory links, it is determined that, if 2 X 10^8 stimuli is received by the body then half of these stimuli, 10^8, will be transmitted as information, but *to where* and *in what form*. The process is: light reflected off of objects stimulate the photoreceptors of the eye, the photoreceptors communicate via electrical and neural discharges to the human cortex, which registers what is seen, and with additional electrical and neural discharges the cortex enjoins the mouth and larynx to engage in speech, and words are then spoken and enregistered by the telephonic device, which represents its interpretation, the successful transmission of information, in a series of pips, as follows:

light-> electricity -> (brain) -> electricity-> words -> (device) -> pips

This is the experimental method to ascertain how much information is lost and dissipated as noise in the physiological process by which information is transmitted to the cortex — and yet, observe the role of the telephonic device to understand how information is corrupted in the Human nervous system. The device, in its terminal position in the chain, is substituted for the cortex as the final, determinative site to which information is transmitted and from which information is sent out. Error in the nervous system can *only be understood* with reference to machines that man has built, because, coextensive with the human nervous system, computing machines also exemplify the impossible task of identifying *which neuron* is responsible for failure or *which neuron* is responsible for an idea. "Rarely do we know enough of the details to guess what we ought to expect or where we ought to look, when we record directly the electrical pulses of the working brain."[86] When the emergence of an idea from the brain is discussed in McCulloch's work it is described as an "invariant."

> When a brain has an idea, we know that there is some invariant in its activity. It may be a succession of signals in time over a single neuron, as in the case of reverberant memories, or the canonical value determined by a reflex, or merely a position in a mosaic, as in the last (read: vision example, especially the determination of size) example.[87]

Encountering the nervous system as a whole, it is impossible to identify which neuron dropped out of normal activity to cause an ensuing thought: "Hence, unless we know something of the net, it is clearly impossible to guess what sort of invariant implies a given idea." Describing the imprecision inherent in the attempt to locate the origin of a thought gives way to describing the imprecision inherent in the attempt to map the wiring of the ENIAC, the electronic numerical integrator and computer at the Ballistics Research Laboratory, *which is also a*

---

[85] Ibid., 375-6

[86] Ibid., 374

[87] Ibid.

description of the necessity of neuroplasticity and the distance between the gene and a neural connection.

> But the story of ENIAC – the electronic numerical integrator and computer at the Ballistics Research Laboratory – is equally scandalous. It is so complicated that no one knows its entire blueprint, and certainly no one knows if it is wired according to that blueprint. In the case of our own brains, it is certain from the chemistry of our chromosomes that our genes cannot specifically determine all the connections of our neurons. What they do is to specify a relatively simple machine, which goes on to build a more complicated machine, which elaborates a third, and so on, until the last prescribes our most complex structures, like the cerebral cortex.[88]

The story of the electronic numerical integrator and computer as "scandalous" is the story of the inability to associate a given neuron with a given thought. The imprecision inherent in the machines man has built comes in to stand for the imprecision of the biomolecular reality driving the human's own morphogenesis: the discussion of genes and the origin of the cerebral cortex.

IX. Cybernetics as a developmental biology

In *Refiguring Life*, Evelyn Fox Keller emphasizes how the problem of an organism's development was considered *a problem for cybernetics* even after the discovery of DNA. She cites the zoologist Michael Apter, who "offered a more sustained plea for the rigorous marriage of cybernetics and development" and who integrated ideas from cybernetics, systems dynamics and automata theory to argue that "genes alone cannot suffice to explain embryogenesis" and that "one way or another, the entire organism must be involved."[89]

The development of the cerebral cortex in its embryonic stage is described in "Of Digital Computers Called Brains" as follows: "a relatively simple machine … goes on to build a more complicated machine, which elaborates a third, and so on, until the last prescribes our most complex structures, like the cerebral cortex."[90] The central idea underlying these progressive, developmental stages is that the continual self-generation of higher order machines from lower order machines specified by the genes results in the cerebral cortex. The incomprehensibility of the electronic numerical integrator and the computer's wiring is tantamount to the incomprehensibility of how neurons connect to one another in the brain. The unknowability of the central nervous system is understood in McCulloch's work as the unknowability of machines – the unknowable wiring of the machines we have made and the unknowable iterations of the machines that make us. And the essence of the unknowability, as the cause of this unknowability, is a specific biological notion of independence. As McCulloch writes:

---

[88] Ibid.

[89] Evelyn Fox Keller, *Refiguring Life: Metaphors of Twentieth Century Biology* (New York: Columbia University Press, 1996), 102.

[90] McCulloch and Pfeiffer. "Of Digital Computers Called Brains," 374.

> Von Neumann has suggested that the plan is something like this: the earlier machines are never completely superseded or separated from the final machines. When they find any part preoccupied or out of order, they shift the problem to be solved to portions of the newer structures of the brain that are free and able to solve it.[91]

The brain's plasticity depends on the lower order, first machines to discover dysfunction. These less complex machines shift the problem of a preoccupied or out-of-order part to newer less preoccupied parts of the brain. This neurological plasticity is compared to the automatic shift that occurs from areas of lower to higher functioning in the differential analyzer:

> This trick is old among the builders of computing machines, and is already automatic in the differential analyzer at MIT. For a minimal computing machine of a few thousand relays, which does nothing in parallel channels, von Neumann estimates that one error in 10^12 unitary operations is tolerable. The best modern electromagnetic relays fail about once in 10^9 operations and neurons far more often. Neurons cannot be replaced. But there are many of them. Consequently, we find that brains perform most operations in parallel, many times over, and then demand agreement before passing on their signals. For all these reason, large numbers of neurons may be dead and gone and the answer may come out correct.[92]

The brain's amendments for itself, its anatomical corrections (coincident circuits, parallel channels, and plasticity) in response to error are capable of being imagined only in the terms of digital computing machines: "the best modern electromagnetic relays fail about once in 10^9 operations and neurons far more often." Neurons fail in relation to relays failing, and they fail more. This is also McCulloch's clearest discussion of parallel operations ((2) parallel channels, where through different paths - and perhaps, in different regions of the brain - the brain executes an identical activity. The anatomical resource that makes this simultaneity possible is the number of neurons, which are legion: "large numbers of neurons may be dead and one and the answer may still come out correct." I interpret this thinking in the following way:

Machine -> computation. Dead neuron -> computation, still.

The mechanism by which the central nervous system recovers from any one neuron's failure – its death – is accounted for in reference to digital computing machines "and the answer may come out correct." I identify here how, in McCulloch and Pfeiffer's brain-computer analogy, incompleteness in the things humans have built serves as a conceptual frame for some incompleteness in the body, in the brain and in the spinal cord. As for how the body rectifies such insufficiencies, McCulloch and Pfeiffer cite von Neumann's theory of proteins as self-reproducing automata, one of the early protein theories of heredity.[93]

---

[91] Ibid.

[92] Ibid.

[93] Lily Kay, *Who Wrote the Book of Life?: A History of the Genetic Code* (Stanford: Stanford University Press, 2000), 108.

"Of Digital Computers Called Brains" was published four years before Watson and Crick's paper on the structure of DNA. Prior to the publication of Watson and Crick's paper, the composition of a cell's hereditary material was an unresolved question, with many members of the scientific community believing *proteins* to be the molecules passed from an organism to its offspring. One of the proponents of the protein hypothesis was von Neumann. The concept of an ever more complex chain of self-reproducing machines that aid in the brain's ability to direct the flow of information away from preoccupied, out-of-order regions to those regions capable of participating in the depolarization events required for the generation of action potentials at a certain frequency requires a kind of linearity, where *only* machines of some minimal degree less complicated than the cortex can build the cortex – and not those that are significantly less complex. What is it about the stage of complexity that allows an embryological machine to build a machine that is slightly more complex than itself? What also, does this say about the relationship between man and the machines that man builds?

One response offered by "Of Digital Computers Called Brains" is that this statement on neuroplasticity is also a statement on time, an instance in which time is conceptualized apart from its status as variable in the logical calculus (f(t)). It is time that instantiates the linear pattern where machines of increasing complexity are produced by machines that are themselves more complex than the machines that produced them. The development of the cortex happens in the womb; the process of differentiation, whereby cells attain a level of organization that allows for the division into specific tissues and then, organ system — is embryological. It is time in this instance that *allows for complexity*. This is an embryological time as opposed to the time that is the independent variable in the function that models the transmission of the nervous impulse. Complexity is not an instantaneous quality – it accrues, in evolutionary time, over generations, and in a mimetic transposition of evolutionary time upon a single human life, it accrues in the cortex, as some part of the nine months spent in the womb. Complexity is an idea innately tied to ideas of evolution, specialization and fitness, and this comment on the cellular mechanics behind neurological changes is all the more curious for the fact that the comparison of man to machine is most useful to describe failures (the need for corrections) of a like kind.

X. Memory and the deception of the machine as a hope

An additional question remains: how pathology differs from memory in this system, how the regenerative quality of pathological circuits might differ from the regenerative quality of circuits responsible for memory,[94] and how the biological basis for memory clarifies McCulloch and Pfeiffer's discussion of time and the function of reflex, where the world implied by the chain of relay signals projects only in the past: "Notice also that the domain for [the] implication of signals extends only into the past." The concept of memory is introduced in a critique of free

[94] Note here the use of the governor of the steam engine as metaphor: "So much for the regenerative closed paths of memory. All other paths are normally inverse — that is, they work on the general principle of the governor of a steam engine. When the engine is running faster or slower than a certain level, the governor senses the discrepancy and more steam is fed into the boiler or released from it. Similarly, each inverse path of the brain establishes some state or level for its system, by bringing the system back toward that state whenever there is a displacement in any direction. The established state is the end in and of the operation of its system. This is the fundamental nature of the function." McCulloch and Pfeiffer, "Of Digital Computers Called Brains," 373.

will. Addressing the anatomical conditions for maintaining responsiveness to a sensible world, they describe how efferent impulses play upon servomechanisms and in so doing, allow for a coordinated response to stimuli applied by physicality about us.[95] To persist in a world requires adjustment to that world. The possibility is raised of a shortcut where "impulses descending from our brains" through shorter paths possess feedback loops activating peripheral and afferent neurons that are somehow prior, prior in time, capacitance and efficiency; such neurons serve as competitors of other, secondary neurons – those associated with the physical responses we *intend*: "the impulses coming by … shorter paths may so determine that something else may happen instead of what we intend."[96] Servomechanisms associated with stimuli-response have feedback loops through which impulses coming by shorter paths (afferent, peripheral neurons) can overrule our will.

There is a possibility that the impulses communicating via these shorter paths determine our behavior and not those communicating via paths associated with our intended response. The concept of free will in McCulloch's system begins from this distinction (what we will versus what we end up doing): "This compels is to distinguish between what we will and what we shall do and in facing this distinction has created the notion of the will." McCulloch and Pfeiffer then locate the distinction within computing machines, which "will be confronted with a similar difficulty"[97] – the difficulty in the human nervous system being the loss of intention's control of the body's responsiveness to the world. Neurons constituting loops of shorter paths become prior, and more efficient for descending impulses to play upon. This "similar difficulty" present in the structure of computing machines, electromagnetic relays arranged in circuits understood as nets and modeled mathematically as matrix functions, also presented the possibility that machines will have wills of their own when a like kind of intention versus actuality distinction arises.

Memory emerges in McCulloch's work as part of this free will argument, in the form of the machine's experience of the distinction between intended and actual outcome, the distinction between the intended and recorded code. McCulloch offers what follows: "When we build computing machines that can compare what they intend with the record they make for us to read, they will be confronted with a similar difficulty and may then be said to have wills of their own." The computing machine's record is the equivalent of our reflex response in the comparison of the computer's intention with human intention – the doing (what we will versus what we shall do), is, for computing machines, the code. I am marking here how the relationship underlying the concept of memory in McCulloch and Pfeiffer's work is the *symbolization* of one's own behavior in code; the edge of this relationship is the most pressing, where some behavior of the machine goes unrecorded and is only apparent in the registered set of the machine's processes – "the record they make for us to read"[98] – after it induces an effect. Coding, here encountered in the analysis of memory as a phenomenon of cybernetic biology, is separate from the notion of coding that, later in the history of science, will be used to describe the production of proteins from DNA. The computer's record, its code, is not a requirement for future forms, but a record revealed for reading upon the application of the right stimulus.

---

[95] Ibid., 371.

[96] Ibid.

[97] Ibid.

[98] Ibid.

The concept of memory is introduced in a discussion of the computing machine's preference over its own record-bearing medium — magnetic tapes or punch card? McCulloch and Pfeiffer claim that ultimately the *preference* of computing machines is for a record that is a palimpsest — preferring magnetic tapes to an irrevocable punch in a card because one has signs that may be discreetly erased and retouched. When they state that computing machines are confronted with a *similar difficulty* as we are what is meant is that computing machines are confronted with an awareness of the difference between intended actions and actual actions. Their actions are to generate signs, and so computing machines possess awareness of generating signs counter to the ones they intend to generate. The authors say that the two irreconcilable sets of signs lead the computing machine to need to erase and re-generate parts of their record, which simultaneously bears and is its activity. The discussion of dependence – "we… require similar discretion of them in… the use of their… memories," and deception – "they… reject all but the one wanted"— necessarily qualifies any idea of free will that emerges from McCulloch and Pfeiffer's text.[99] The consistent ability to perform an intended set of actions is a mechanical and anatomical *question*. So any intention, any discernment related to intention, and any real disobedience, seems a hope rather than a criticism.

Here, the distinctions between intention and actuality are what lead to an assessment of the machine possessing *will*, free will, also leads to the possibility that machine's have preferences over the composition of their own process, the registering of their behavior: "This may lead them to prefer magnetic tapes or wires , whose signs may be erased, to an irrevocable punch in a card. At the moment, this may sound far-fetched, but we are beginning to require similar discretion of them in the use of their own long-storage memories, whence they may recall items and reject all but the one wanted."[100] This will lead to the machines having *preferences* over a transcript that can be changed after the fact. The machine's ability to alter the record after the initial inscription of the memory serves as hope because, somewhere in the wires, where the flesh meets the world, we are there, too. Still somehow capable of expressing autonomy over our reflexes.

XI. The three types of memory of biological, medical cybernetics

McCulloch proposes three kinds of memory based on the technologies of memory demonstrated by computing machines :

(1) reverberating chain memories: a closed path of non-overlapping relay circuits – "relays like the rest of the circuit, but arranged in a closed path of sufficient length so that the beginning and the end of a train of signals running around the loop do not overlap"[101] to employ a natural metaphor to aid in understanding, this is like the reducing loop of a snail shell. The necessary conditions for the memory functions of reverberating chain memories to be effective are (1) a physical extension for storage (2) a path into the storage so stored information can be retrieved by the system. "The reason is that, to be effective, there must be

---

[99] Ibid.

[100] Ibid.

[101] Ibid., 371,

a way from the computer into the storage, and from the storage back to the computer, which effectively completes a path around which the information goes."[102]

(2) the memory responsible for skilled acts, for example the "soldering-in of a multiplication table."[103]

(3) the memory that includes sense-experiences: "memory preserves for us a record of things sensed but once in passing." The metaphor that McCulloch offers is that of a chronological ordering of photographs, "snapshots in the order in which they were taken", where access is in reverse order if access is gained at all: "but found with difficulty if at all in the reverse direction."[104]

The discussion of memory begins with the discussion of the *modern digital machine's* memory, the structure of which we share, and ends with the discussion of two memory functions unique to human beings.[105] The implications for any discussion of the first type of memory, relays like those in other circuits but arranged in a closed path of length such that the beginning and end of signal bearing parts do not overlap, regarding the durability of form, as an anatomical translation of a transient world. The world makes demands, "the world that did impinge upon our sense organs" and McCulloch and Pfeiffer, building on the proposition of Lawrence Kubie and the research of Rafael Lorente de No, describe (1) the event and the (2) its anatomical reverberations as form, or figure, granted by a set of impulses that regenerate in a pattern identical to the pattern caused by the stimuli of the event: "a train of impulses, patterned after some input may continue to circuit as long as we please; as long as it lasts, it continues to reiterate in the form of its input the thing sensed." There is no temporal marking of the continuous reiteration in the form of the input of the things sensed. McCulloch submits that the figure or form that serves as the anatomical remainder of the event circulates without reference to time: "we know that there was some event which was of that figure but we have thrown away its exact position in time."[106] Furthermore, the reverberating chain memories of calculating machines which provide the technical basis for modeling human memory are described as ultimately less complex than the biological reverberating chain memories they represent.[107] The relays, metal and plastic and glass filaments and wires, are *inefficient* when compared to the neuron in respect to the memory function. McCulloch and Pfeiffer, comparing man-made relays to the cells of the nervous system, note: "Man-made relays are too expensive, large and fast, an inefficient to be used like neurons for reverberating chain memories." And yet, reverberating chain memory is the model of memory in general: "but no-one of these devices does anything

---

[102] Ibid., 372.

[103] Ibid.

[104] Ibid., 371.

[105] "Modern computing machines have several kinds of memory." Ibid., 371.

[106] Ibid.

[107] "The memory devices of calculating machines are acoustic tanks, cathode-ray tubes with screens of various persistences, and many other instruments which clear themselves completely when they are shut off. But none of these devices does anything that cannot be done by reverberating chains and this holds true for every kind of memory-whether it is born in us or made by us-even for the marks on this paper." (372) Ibid., 372.

that cannot be done by reverberating chains, and this holds true for every kind of memory – whether it is born on us or made by us – even for the marks on this paper."[108] As for reverberating chain memory: it is the formal model of memory based upon the McCulloch-Pitts neuron offered in "A Logical Calculus," which itself is based upon Whitehead and Russell's argument that certain mathematical function corresponds to the continuous circulation of a certain idea, where the universal or the idea (a given memory) is the figure of the input, a patterned form springing up from a given array of sensual stimuli, always in the same way. What this also means is that the function is the figure of the input and means that any stimuli in relation to that thing(the original event) will be of that figure, will be of that functional form, no matter *when it happened or whether it was chronologically identifiable as the original event or not*.

---

[108] Ibid.

is called a universal, or idea. In our example, it is the figure of the input, and x can take the meaning "any event which was of that figure, regardless of when it happened." $\exists(x)$ simply asserts that there was some x. By combining this assertion with negation, we get—for example—$(\exists x)(\sim\phi x)$, which means the same as $(x)(\phi x)$. Both expressions say, "For all x's, x is of the figure ϕ." It is for this reason that we may regard ϕ as a universal.

Figure 3: Memory in the model of the McCulloch-Pitts neuron
From: Warren McCulloch and Walter Pitts, "A Logical Calculus of the Ideas Immanent in Nervous Activity" (1943)

The two final sentences are the most significant: any given event (x) belongs to a figure that is universal. By *figure* what is meant is *function —* which in its universality, is applicable across cases. The function holds it or it does not. The memory is present or it is not. This is a stimuli-present/stimuli-absent model. Overall, if the memory is present within the circuit, if any stimulus related to the original event is *there,* it exists in this (the original memory's) form. As for what memory *is* —it is not a sensation, nor a set of words that narrate filmic images, nor the images themselves, it is a *figure* a *form*, which is best understood as the pattern of signals that reverberate or re-circulate within a closed loop. The memory of digital computing machines is what allowed a formal model for *all memory, "whether born in us or made by us" :*"The memory devices of calculating machines are acoustic tanks, cathode ray tubes with screens of various persistences, and many other instruments which clear themselves completely when they are shut off. But none of these devices does anything that cannot be done by reverberating chains, and this holds true for every kind of memory – whether it is born in us or made by us – even for the marks on this paper."[109] Reverberating chains in any technological or biological system can do all that reverberating chains in calculating devices do with regard to memory. Memory as a function is transposable, across the technological and biological system, but what secures the possibility of memory is very different for each and gives cause for the writing of this dissertation: the question is if the process is identical what *kind of substrate*, *what is not hardware but flesh*, is the brain such that it participates in and regulates life-processes. What does life need to *be* for the brain to work this way? Somehow, the description of memory seems to be also full of dread nostalgia, where memory is as an entirely human stack of photographs that one works through. In this close reading, the descriptive and technical particularities, furnish details of how McCulloch and Pfeiffer were considering biological life and the relationship between memory and experience.

For the following types of memory:
(1) the memory responsible for skilled acts, such as the memory of a multiplication table
(2) the memory that preserves a record of transient sensory experiences, such as in a stack of chronologically arranged photographs.

McCulloch and Pfeiffer cite John Shroud and Heinz von Foerster in a discussion of half lives, neuropathology and how protein molecules might be the carriers of memory. About the

[109] Ibid., 372.

memories associated with sensory-transient memory, McCulloch & Pfeiffer offer that they resemble a stack of photographs or snapshots stored in the order in which they were taken to summon a sensory experience that is placed in time due to the placement of the photograph that summons the experience. These photographs are said to be 'earmarked' or marked for recall on the basis of certain properties.[110] The computing machine accesses the storage of such memories, with difficulty just as a person would, thoroughgoing, access a stack of photograph in reverse order of the order in which they were taken (top of the stack -> bottom of the stack, most recent -> most dated). Citing Shroud and von Foerster, McCulloch submits a *size* for the physical storage associated with the memory function based on how many bits of information as "picture snaps" there are over a lifetime: "From the work of John Stroud, of the U. S. Navy, it seems that we would have a chance to "snap" about 10^10 such pictures in a normal life and, if each had any reasonable content and a thousand ways of recalling it, human memory must have storage space for some 10^13-10^15 bits."[111] The physical media and the role of physical ordering to communicate information cannot be ignored. His is a digital model for the functioning of memory - an idea iterating in a mathematically patterned way - and yet physical media serve as analogies for the model's components. Almost as if a model that is virtual, that cannot be "filled in" or earthbound or tethered to the hand that produced it - its content is also virtual, but its components, or what slips and works within the model - the bit, the memory, the finding, the finger - can be, meaning, they can be understood by way of an analogy of the things of this world, which *can* hold information by their place in an order. Alva Noë, philosopher of mind, offers the following: "In this way, we can appreciate that technology extends not only what we can do. It extends what we are. Our minds bleed out of our heads onto the paper and into the world."[112] Noë cites the influential essay on the "extended mind" by philosophers Andy Clark and David Chalmers, describing their work as posing the question: "where do you stop and where does the rest of the world begin? There doesn't seem to be any principled reason to think the stuff going on inside our heads is privileged in comparison with the stuff we write on paper. Both are necessary for the kinds of thoughts we have, for the kind of thinking and problems that interest us." The idea that technology can become extensions of the human sensorium[113] is not a new idea but here, it is refigured in the terms of philosophy of mind, in the terms of how separate and away from us are the things we *build* from the things we *think*. And what connects virtual technology to the physical technology it moves through.

McCulloch discusses technology in terms of its approximations of the body's physiological processes in the paper, "The Biological Sciences" (1966) in a discussion of how scientists could possibly detect the presence of life on Mars: "today there are machines teaching differential diagnosis and there are prospects of automated clinics as well as artificial pacemakers for failing heart and artificial kidneys. Every simulation sharpens the biophysical problems and

---

110 "In several ways it resembles a stack of photographs or snapshots stored in the order in which they were taken, but found with difficulty-if at all-in the reverse direction. They seem some-how to be earmarked so that, like the punch cards in a machine, they can be selected or recalled on the basis of common properties. Judging by the number of such similarities at our disposal, our snapshots must be earmarked in many hundreds of places." Ibid.

111 Ibid.

112 Alva Noë, Alva. *Strange Tools: Art and Human Nature* (New York: Farrar, Straus and Giroux, 2015), 27

113 See Marshall McLuhan, *Understanding Media: The Extensions of Man* (New York: Penguin, 1966).

discloses any inadequacy of our conception of the function in question."[114] From the work of Heinz von Foerster, McCulloch and Brodey refer components of the memory model by its traces and had lives, where memory must be in equilibrium with access and exit points. Answering the question as to the size of human memory:

> The physicist Heinz von Foerster, from a study of the curve of forgetting of nonsense syllables and running faster or slower than a certain level, the from very general considerations based on biology and quantum mechanics, came out to be about the same number. He points out that if we know the mean half life of a trace, or stored bit (which in us is half a day), the half life of our signals for access to and egress from the storage of the traces and the number of parallel channels in and out of it - then we know how large that memory must be to exist in equilibrium with the access and egress. It is simply the number of parallel channels in and out (10^7) multiplied by the ratio of the half life of the trace to the access time, both in seconds (10^5 and 10^-3, respectively), or 1015 places for stored bits of information.[115]

The second sentence is a mathematical rendering of how large that memory must be, and significantly, physiology is brought in: "Reasonable considerations for the stability of each such bit would allow it about 10^5 or 10^6 possible loci in its cells, making a total of something like 10^21 loci in the brain". Meaning, the requirements of bit storage and memory size and half lives can be met by the biochemistry of the brain, because (1) enzymes in the brain are resonant at the proper wavelengths and (2) the brain has the number of protein molecules an enzymes sufficient to maintain the level of energy required by the memory function — the energy requirements within the brain for maintaining *traces* that earmark memories can be met with the number of *proteins* and *enzymes* (at the time a sub-category of proteins) we know to exist in the brain:

> A half life of half a day gives an energy per step of somewhere in the first or second octaves in the infrared and a total power to maintain traces of the order of a hundredth of a watt. All these specifications could easily be met by what we know of brains whose enzymes are resonant at the proper wavelengths and the number of whose proteins molecules is several times 10^21.[116]

This is the first reason and second reason to suspect proteins as the causal agents in memory formation. The third (3) is the argument that because protein molecules are the only molecules that have the ability to regenerate themselves, logically, they should be responsible for memory formation which results in some things memories, which are never forgotten. A fourth (4) reason for suspecting protein molecules is that compounds that denature proteins affect memory loss. In terms of memory formation as accounted for by some regenerative process capable of multiplying traces before they fade, McCulloch and Pfeiffer offer the following about

---

114 McCulloch and Brodey. "The Biological Sciences," 292.

115 McCulloch and Pfeiffer, "Of Digital Computers called Brains," 372.

116 Ibid.

the physical processes induced by nucleoproteins, which have curves of decline with an asymptote at 0%:

> But von Foerster presents a second reason which makes us suspect protein molecules. Whereas all ordinary physical processes have curves of decline which approach zero asymptotically, the curve of forgetting approaches asymptotically a residual value of several percent. In other words, some things are never forgotten. This can only be accounted for by some regenerative process capable of multiplying traces before they fade, and only protein molecules – nucleoproteins, to be specific – seem to possess the ability to generate others templates after themselves.[117]

The clinical evidence for reason (4) where proteins drive these regenerative processes that constitute memory because when these proteins are destroyed by lead or alcohol, memory suffers, such as in the case of Korsakoff's syndrome: "Moreover, clinical evidence indicates that protein denaturants destroy memory, most clearly so when alcohol, lead, or other poisons attack an old central structure of small neurons, whose destruction produces the famous Korsakow's psychosis and makes it impossible for animals to learn."[118]

XII. Conclusion

In "Of Digital Computers Called Brains," proteins are the causal agents behind both memory and development. Proteins of ever-increasing complexity are built from those of lesser complexity, resulting in the development of organs within an embryo, and proteins of certain energy thresholds regenerate memories, as they are able to regenerate themselves.

I have focused on the molecular aspects underlying the brain-computer analogy: physiology of perception, the physiology of development, and the physiology of memory. There is an origin story, here, apart from the story of proteins reproducing themselves as ever more complicated machines, apart from the structure of the delivery of size and form to consciousness when a light ray hits a retina. In *Refiguring Life*, Fox Keller identifies *what could unify physics and biology* during this period besides theories of vitalism, namely an *extension of the perimeter* of the living system. As she explains: "if one redraws the boundary of the living system, not at the outer skin of the organism, but at the outer perimeter of a closed thermodynamic system large enough to encompass the energetic substrates required by metabolism, the problem might be said (and indeed was said) to vanish."[119] Seeing the world as living is one way to reconcile the activity seen in nature and and the activity demonstrated by the body, and by machines in analogy with that body; however, what's clear in McCulloch and Pfeiffer's rendering of life in "Of Digital Computers Called Brains" that life is not a *life force* it is, instead the perceived relationship between matter and world susceptible to the same forces.

---

[117] Ibid.

[118] Ibid.

[119] Fox Keller, *Refiguring Life, 65*.

Chapter 2: The Pharmacological Model of the Brain in McCulloch's Animal Experiments

Having analyzed how McCulloch and Pfeiffer's electrical model of the brain includes perceptual requirements for life, I now turn to McCulloch's animal experiments to understand how the brain was understood when it was firstly an organ connected with other organs in a *living system*. His animal experiments encounter the brain as a physiological structure. His animal experiments, which encounter the brain as pharmacologically measurable, do not diminish the relevance of the computing problem but instead, the esophagostomies and the dosing of cats, reveal how the perceptual requirements for life are adjustments the organism makes or adjustments that the physician induces in their care for the patient.

Georges Canguilhem's discussion of biological normativity in his influential *The Normal and the Pathological*, invokes a specific relationship between the organism and its environment, where the organism is understood as normative for its ability to maintain norms or to *establish* new norms after breaking them.[1] When Canguilhem submits a definition of life, it is within this context of vital norms and pathological norms, "there are healthy biological norms and there are pathological norms, and the second are not the same as the first," where the summed pattern of an organism's activity can be evaluated with reference to vitality and disease. And even simple metabolic systems, like the oxidation of blood sugar, can be assessed in these terms, as possessing positive or negative value:

> The simplest biological nutritive system of assimilation and excretion expresses a polarity. When the wastes of digestion are no longer excreted by the organism and congest or poison the internal environment, this is all indeed according to law (physical, chemical, etc.) but none of this follows the norm, which is the activity of the organism itself. This is the simple fact that we want to point out when we speak of biological normativity.[2]

Such a polar, metabolic system is, I will argue, what is being explored in McCulloch's experiments, and in these experiments we see the development of a concept of *world-building,* in which the nervous system prepares the organism for future, normal states of life. Central to the concept of life will be the chemical premise of nutrition.

Certain variables (levels of glucose, acetylcholine, cholinesterase) could be used experimentally to determine the role the brain played in micro functions as in the regulation of blood sugar and macro functions as in the regulation of behavior. This brain, responding to chemical stimuli and the particular shapes of enzymes, is a pharmacological brain in that its activity can be traced from the the body's adjustments to the presence of certain chemicals. It may seem unusual to explore a therapeutic cybernetics, but as evident in his research on schizophrenic cats and in the research of McCulloch's colleague, Ellen Ridley, in synthesizing

---

[1] "Normative to the fullest extent of the word is that which establishes norms. And it is in this sense that we plan to talk about biological normativity." "In short, physiology would be only one sure and precise method for recording and standardizing the functional freedoms acquired or other progressively masted by man. If we can speak of normal man as determined by the physiologist, it is because normative men exist for whom it is normal to break norms and establish new ones." Georges Canguilhem, *The Normal and the Pathological,* tr. Carolyn Fawcett (New York: Zone Books, 1989), 127, 165.

[2] Ibid., 129.

cholinesterase, there were ideas of cure and of treatment in this biological, medical cybernetics left unaccounted for in readings of the cybernetics in the post-war period that privilege the developments in artificial intelligence, automaticity, and the symbolic and mathematical presentation of biological behavior. McCulloch was a clinician, and this second chapter reveals the degree to which notions of therapy were intrinsic to the perceptual life facilitated by the nervous system. The brain, while being electrical, was also a pharmacological project. The chapter closes with a discussion of McCulloch's notion of homeokinesis, a revision of Canon's concept of homeostasis, where McCulloch account for the additional variables that the organism needs, a concept of life not only in terms of an equilibrium but in the terms of time and space: the time of response and the space to be chemically acted upon and changed.

The pharmacological brain begins from a method of analyzing excess — too much sugar in the blood — but, like Canguilhem's discussion of the normal and pathological in relation to value,[3] McCulloch's pharmacological brain explores how and why the brain privileges certain roles for itself and how the brain can be reminded, through an adjustment of its chemical environment, of what roles once mattered.

In a letter attached to his C.V., sent in 1941 to Percival Bailey at the University of Illinois School of Medicine, McCulloch wrote that the condition, neurosis, will only be understood by approaching the organ, the brain, like any other organ. McCulloch wrote, in reference to the care-taking of patients on Ward Island, where a psychiatric state hospital had been in operation since 1848[4]:

> From the time I was studying psychology and philosophy in college through the time I was working for my M.A. in psychology in Columbia – actually largely in psycho-pathology including work on Ward's island – and all down these years in the lab, my interest in psychiatry as been ever present, for I am convinced we will get nowhere with crazy people until we can understand brains in such physico-chemical terms as we use when thinking of the kidneys.[5]

McCulloch suggests both a physical and chemical approach to understanding the brain so to understand psychiatric pathology, "we will get nowhere with crazy people." The reference to the kidney, beyond being a reference to an organ like any other, is also a specific reference to chemical *homeostasis*, a reference to metabolism and the use of sugars for energy. It is a reference to nutrition, to what the body has ingested, as the kidney is the site where the chemical concentration of internal electrolytes is maintained. Considering a chemical basis – and not solely an electrical basis – for nervous activity requires a system capable of physically sensing the world inside itself: blood sugar, pharmaceutical compounds come from elsewhere to circulate within and inhabit the blood. I argue that McCulloch's chemical questions applied to the brain in a series of animal experiments conducted at the Illinois Neuropsychiatric Institute, reveal an

---

[3] "A living being is normal in any given environment insofar as it is the morphological and functional solution found by life as a response to the demands of the environment. Even if it is relatively rare, this living being is normal in terms of every other form from which it diverges because in terms of those other forms *it is normative*, that is, it devalues them before eliminating them" Canguilhem, *Normal and the Pathological*, 144.

[4] J. F. Richmond, *New York and Its Institutions, 1609-1871*. (New York: E.B. Treat, 1871), 551.

[5] Quoted in Tara Abraham, *Rebel Genius: Warren S. McCulloch's Transdisciplinary Life in Science,* 73.

anticipatory nervous system that prepares for and recognizes metabolic encounters with the world, a system that ciphers and marks the process of crossing over. Whether by the state of degradation of the compound or the pathway or the mode of entry, the world's materials are sensed by the nervous system — less as a definitive marker of world versus self but as the conscious recognition of a process of bringing the outside in, in a manner that is constitutive, transformative. And this recognition brings solace, as easily discernible as the feeling of satiety after eating.

I. A chemical origin for disorders of the nervous system

In *Capital*, Marx writes of the act of laboring as an encounter with nature, where the work on nature's materials reveals nature's force:

> Labour is, first of all, a process between man and nature, by which man, through his own actions, mediates, regulates, and controls the metabolism between himself and nature. He confronts the materials of nature as a force of nature.[6]

Marx is useful when analyzing McCulloch's idea of the nervous system, given Marx's reference to force and his discussion of metabolism as a confrontation. The force of the materials of the world, Marx's materials of nature, can be therapeutic in McCulloch's biological, medical cybernetics, considering the use of pharmaceuticals in the chemical treatment of neuropathology. I argue that the confrontation inherent in metabolism presents itself in McCulloch's system as a moment of recognition by the nervous system of a chemical process and not a state of being self or other.

The Kreb's cycle for the oxidation of glucose was discovered in 1937. McCulloch was conducting chemical experiments on the nervous system in the wake of the scientific community's realization that glucose is involved in a pathway, a feedback-loop after the moment of ingestion, where glucose, the world's material, would be degraded in a modulated fashion, where each metabolite is a reference for each other in the pathway. This is to say that, from McCulloch's experiments, we can see that the nervous system does not register glucose discretely, that is, does not register the identity properties of self and other, but rather acts like it recognizes the possibility for one becoming the other.

II. Animal experiments at the INI, integrating material physiological and philosophical considerations of the brain

From 1941-1952, McCulloch was affiliated with the University of Illinois School of Medicine where he worked as a professor of Psychiatry and director of the Illinois Neuropsychiatric Institute (INI).[7] McCulloch's rationale for joining the Illinois Neuropsychiatric Institute was that the research occurring at the INI was conducted on the premise that pathophysiology associated

---

[6] "Labour is, first of all, a process between man and nature, by which man, through his own actions, mediates, regulates, and controls the metabolism between himself and nature. He confronts the materials of nature as a force of nature." Karl Marx, *Capital*, vol. 1. (New York: Vintage Books, 1977), 283.

[7] Abraham, *Rebel Genius*, 73, 153, 75.

with nervous disorders had a "physico-chemical" basis. After working as a researcher, McCulloch served as the head of the Illinois Neuropsychiatric Institute associated with the University of Illinois School of Medicine. Neuropsychiatry was a crossover field located in some middle place between the fields of Neurology and Psychiatry. At the time of McCulloch's research, psychiatry was a fledging discipline in the process of legitimizing its medical program.As historian and physician Jack Pressman observes, psychiatry occupied a "peculiar position," in the early 20th century, as a "liaison science between society and medical science." Psychiatry emerged from the 19th-century fields of psychobiology and social science, addressing the causes of social disorder, transgressive behavior and suicide.[8]

The Illinois Neuropsychiatric Institute was prodigious, consisting of nine floors of laboratories in addition to a basement laboratory complex. At the INI, McCulloch attempted to integrate (1) biological ideas about the brain as a physiological organ and (2) philosophical ideas about the brain as mind.[9] I argue that the practice associated with this integration is best understood in a series of animal experiments that took place at the University of Illinois School of Medicine from 1951-1953, the results of which were published in "Dog's Blood-sugar level affected by Taste and Sham-feeding" and "Effects of Intraventricular Acetylcholine and Cholinesterase and related compounds in normal and catatonic cats." In the animal experiments described in the papers, qualities are ascribed to the organism on the basis of behavior, qualities like "perceptive" and "catatonic," as well as behavioral states affiliated with homeostatic regulation - states like "thirst" and "agitation" – are studied on a pharmacological basis. I argue that, as represented in conclusions drawn from animal experiments of 1951-1953, the brain acquires its characteristic command-control function – the distinction of its tissues – due to the brain's preparedness for the cellular concentration of certain molecules, understood in the terms of chemical stimuli.[10] McCulloch's experiments concern the brain's chance existence as the site in which chemical stimuli drive the large scale behavior of the organism, and in doing so, I claim, demonstrate a complication of the electrical model of the brain, whereby the nervous system's electrical activity is secondary to its process of sensing and responding to chemical intrusions from a nutritive world.

III. The anticipatory body of the blood glucose level experiments of "Dog's Blood-sugar level affected by Taste and Sham-feeding"

---

[8] See Jack Pressman, *The Last Resort: Psychosurgery and the History of Medicine*. (Cambridge: Cambridge University Press, 2002), esp. 20-1.

[9] Abraham, *Rebel Genius*, 74. Abraham describes how, at the INI, McCulloch's "physiological and philosophical interests merged" resulting in "bold confrontations."

[10] 35. Catherine Malabou presents the cybernetic brain as a one understood on the basis of its command-control function, against which she posits notions of plasticity and invention. "Opposed to the rigidity, the fixity, the anonymity of the control center is the model of a suppleness that implies a certain margin of improvisation, of creation, of the aleatory." Malabou, *What Should We Do with Our Brain?* tr. Sebastian Rand (New York: Fordham University Press, 2008), 35

Two experiments conducted over two years by McCulloch and collaborators[11] at the University of Illinois Department of Psychiatry were published in "Dog's Blood-sugar level affected by Taste and Sham-feeding." Printed in 1953 in the Proceedings of the Federation of American Societies for Experimental Biology, the paper questions the role of the central nervous system in regulating blood glucose levels, as "part of the study of the role of the central nervous system in carbohydrate regulation."[12] The purpose of the experiment was to observe, first, the effects of taste and smell during feeding in a control group, and second, to observe the effects of taste and smell during sham feeding in an esophagostomized group. In sham-feeding experiments, ingestion occurs without providing nourishment to the organism. The archive at the American Philosophical Society Library held only drafts of "Dog's Blood-sugar level affected by Taste and Sham-feeding," but the set of drafts include late-stage drafts of the paper, as well as the experiment's statistics, the experiments' method, and the conclusions drawn from the experiment by the authors. The drafts also include McCulloch's handwritten annotations.

In the experiment of "Dog's Blood-sugar level affected by Taste and Sham-feeding," the sham-feeding of the dogs provided no nourishment because the esophagus, the tube that carries the bolus of food from mouth to stomach, was made to be external to the body. A paper that McCulloch and collaborating authors, Ridley, Share and Berry, cite in "Dog's Blood-sugar level affected by Taste and Sham-feeding," is "Effect of Prolonged Intragastric Feeding on Oral Food Intake in Dogs," which describes the Dragstedt and Mullenix method of esophagostomy, the same method employed in McCulloch's sham-feeding experiments:

> Esophagostomies were performed according to the method of Dragstedt and Mullenix with exteriorization of esophagus in the neck in the first stage, and division by cauterization of the exteriorized esophagus in the second stage 5 to 7 days later.[13]

Food never arrived to the stomach because the bolus exited the body in the esophagus, through a hole made surgically by the researchers[14]. The esophagostomy of dogs was frequently employed as a experimental technique not only in research on gastrointestinal physiology and the vagus nerve[15] but also in research on the relationship between chemical secretions and behavior in, for

---

[11] Ellen Ridley, Isiah Share, M.D. and John M Berry, M.D.

[12] With respect to this article, I am drawing from material in drafts of the article, "Dog's Blood-sugar level affected by Taste and Sham-feeding," in the Warren S. McCulloch Papers, Box 60, Mss.B.M139.

[13] Isiah Share, Eugene Martyniuk and M.I. Grossman. "Effect of Prolonged Intragastric Feeding on Oral Food Intake in Dogs," 1952. Warren S. McCulloch Papers, Box 60. Mss.B.M139.

[14] See John Smith, "Stomach Distension," in *The Palgrave MacMillan Psychology of Food and Eating: A Fresh Approach to Theory and Method*. See also A.W. Logue's *The Psychology of Eating and Drinking* (Basingstoke, UK: Palgrave MacMillan, 2001). Logue is cited in Smith's text for the esophagostomy information. For the experiments described in "Dog's Blood-sugar level affected by Taste and Sham-feeding," the researchers employed the esophagostomy method of Dragstedt and Mullenix, in which the esophagus is taken out of the body in the neck, as described in a paper, "Experimental Esophageal Fistula" published in 1931.

[15] See the discussion of sham feeding in Martin Fischer, *The Physiology of Alimentation* (New York: John Wiley, 1911).

example, Ivan Pavlov's use of esophagostomy as a technique to study the relationship between gastric acid and hunger.[16]

In the experiments described in "Dog's Blood-sugar level affected by Taste and Sham-feeding," the dogs were sham-fed 3ccs of (a) pablum[17] (1:3 parts water) and (b) flavored pablum (1:3 parts water) 30 minutes apart. To measure glucose levels, blood samples were taken at 10 minute intervals during the 60 minute duration.[18] The findings of the experiment were that:

(1) there was a 10% increase in blood glucose levels following unflavored pablum consumption and a 20% rise in blood glucose levels following flavored pablum consumption[19], even given the fact that the caloric content of the unflavored and flavored pablum was nearly identical. Meat extract was used in the flavored pablum[20].
(2) for dogs in the sham-fed esophagostomized group, the results after five minutes were the *same* as for dogs in (1), the non-esophagostomized control group[21]. The dogs who were esophagostomized and merely ingested food (sham-fed) demonstrated the same percentage increase in blood glucose as the dogs who had the physiological capacity to digest the food (a 10% increase in blood glucose levels following the ingestion and taste of pablum and a 20% increase in blood glucose levels following the ingestion and taste of flavored pablum);

---

[16] "Pavlov established a model of sham feeding in dogs equipped with esophagostomy and demonstrated that anticipation of eating stimulated gastric acid secretion." Mitchell L. Schubert, "Central Regulation of Gastric Acid Secretion," in Leonard R. Johnson, *Physiology of the Gastrointestinal Tract,* 5th ed. (Cambridge: Academic Press, 2012), §47.4.1, p. 1281.

[17] I assume that pablum consists of simple carbohydrates and that all carbohydrate absorption occurs in the small intestine.

[18] "Blood samples were drawn at 10 minute intervals from the beginning of the control period until at least 30 minutes after the second taste." "Dog's Blood-sugar level affected by Taste and Sham-feeding."

[19] "One dog showed an elevation of approximately 5% of the fasting blood sugar after the first taste but following this the blood sugar returned to the control level and did not fluctuate. All other animals showed a rise above the control level in the blood sugar after tasting unflavored pablum. All other animals showed a rise above the control level in the blood sugar after tasting unflavored pablum. The average rise was 10%, S.D. +/- 6.2, significant at the 1% level. The rise above the control level was twice as great when they tasted flavored pablum. The average was 20%, S.D. +/- 10%, significant at the 1% level." Ibid.

[20] "A test run consisted of 45 minute control period after which the dog was allowed to taste 3 cc. of an unflavored mixture of one part pablum and three parts water; thirty minutes later, the dog was offered a similar quantity of the same mixture flavored with meat extract." Ibid.

[21] "Blood sugar samples taken during sham-feeding showed the same rise as had been found in the experiment on the effect of taste alone. Five minutes after shame feeding each dog on every test had a fall in blood sugar exceeding the fluctuation from the fasting level." And "During sham-feeding blood-sugars rose as described for taste, but 5 mins. later, always in every dog, fell more than his largest fluctuation of fasting level. Nadirs were constant for each dog at 10 or 20 mins. after sham-feeding. Average fall was 17%, S.D. 5.6%, significant at 1% level." Ibid.

> however, blood sugar levels fell precipitously after 5 minutes in the sham-fed dogs, in a 17% decrease from pre-experiment fasting levels.[22]

The emphasis is on how *taste alone,* taste without nourishment, is capable of increasing the blood sugar levels of the dog, even if, five minutes later, blood sugar plummets. For five minutes, the esophagostomized dog's body, after merely tasting food, demonstrates the same increase in blood sugar levels as the body with an esophagus, the dog capable of ingesting the food it had tasted. McCulloch & collaborators, Ridley, Share and Berry, are cautious in rendering their conclusion:

> These experiments are not such as to reveal the mechanism underlying the observed effects and consequently, no hypothesis is here proposed. We can only conclude that taste, especially of the preferred substance (flavored) causes a significant rise…in blood sugar.[23]

They describe how the mechanism of such tasting-effects on blood sugar levels remains unclear but offer a cause and effect relationship between flavor – even a flavor without nourishment – and changes in blood glucose levels. The case presents several medical lacunae: where is the drop in blood sugar facilitated by insulin in the dogs fed pablum? Why would blood sugar levels initially increase in step with each other, in a dog with no physiological possibility of nourishment and a dog whose esophagus does allow a bolus of food to be passed? And perhaps the most generative, why would blood sugar levels increase during ingestion, within a system in which no blood sugar is reaching the blood?

There is an anticipatory, pantomiming nervous system revealed by these questions. The nervous system mimics a known state, the state of being fed, if just for those five minutes, in anticipation of the chemical inputs that might secure it. In those five minutes, this nervous system is future-oriented, responding to the mere possibility of nourishment and not actual, present-tense feeding, it is also self-simulating, repeating known patterns in anticipation of those patterns being confirmed as a suitable response to the world. I argue that this ability of the body, which, through the central nervous system, is able to project itself into the future, is one of its fundamental world-building capacities in McCulloch's biological and medical cybernetics — here a capacity indebted to the nervous system's ability to pantomime past interrelations between body and world. This is also a capacity possessing a normative quality, as Canguilhem explained, oriented towards future states of requiring glucose for energy expenditure, oriented towards a world that can provide it.

McCulloch and the other authors, Ridley, Share and Berry, acknowledge that the mood of the dogs could influence the body's regulation of blood glucose levels. The authors describe the measures taken to train the dogs to be calm such that mood could be a stable variable and without influence on the experiments' results:

> Excitement and interest as well as fear affect the blood sugar level. The fluctuations of the control level of blood [sugar] previously reported on similar studies

[22] Ibid.

[23] Ibid.

> suggest that some such factors were disturbing the dogs. This we could avoid only by prolonged training until such time as the dogs became sufficiently acquainted with us and the procedures to cooperate fully … the experiments required more than 250 trials and nearly a thousand blood sugar determinations.[24]

The authors controlled for the effects of mood and found that *taste alone* was enough to transiently induce identical levels of blood sugar in a body with a tube to the stomach and in a body without one. Note that this is less about how taste plays "tricks" on the brain than it is about how taste serves as a chemical stimulus for the central nervous system in the regulation of glucose concentration in the blood. The actuality of nutrition is not necessary for the nervous system to begin to respond to the *taste of meat*, the flavoring of the meat-extract.

Other studies at the time focused on large-scale, physical changes in the conception of what is communicated to the nervous system by gastrointestinal fluctuations, in a focus on the physical dislocation of matter and not the chemical interactions attending digestion. What fascinates is the immaterial, almost homeless aspect of McCulloch's net of neurons responding to taste alone, neurons responding to taste even in the absence of a way to the gut, where the nutrition might be further sensed and absorbed. The concept of the neuron this requires is that of a neuron oriented outwards and primed — primed for the sole responsibility of receiving the world at one point of entry. Other concurrent studies pursued how physical alterations of the gastrointestinal tract transmitted information to the nervous system. One example of such a physical alteration would be the distention of the stomach upon feeding. McCulloch's paper, "Dog's Blood-sugar level affected by Taste and Sham-feeding," cites research, also from the University of Illinois Department of Psychiatry, vested in the degree to which a balloon of lesser or greater size placed in the stomach of a dog inhibits or facilitates the dog's feeding as the motivation to eat. Describing such research, McCulloch comments:

> These studies again demonstrate that gastric distention is an important regulatory factor in controlling the amount of food eaten. They also indicate that a systemic factor related to nutritional status (caloric deficit or surplus) also operates but its mechanism is obscure and does not accomplish fine adjustment of intake to requirement.[25]

The research McCulloch led at the University of Illinois Department of Psychiatry on the regulation of sugar in the blood took place in the context of a tension between the consideration of physical changes that induce specific forms of nervous activity - where a swollen stomach communicates satiety, as a way to "controlling the amount of food eaten"[26] - and chemical changes that induce specific forms of nervous activity, where a cascade of molecules, microscopic pieces of the pablum, communicate that fluctuating blood sugar be maintained at a certain level. McCulloch's discussion of the surrender of identifying the mechanism by which blood sugar levels are regulated occurs twice in "Dog's Blood-sugar level affected by Taste and Sham-feeding," and yet I argue that the promise of discovering this mechanism and for

---

[24] Ibid.

[25] Share, Martyniuk and Grossman, "Effect of Prolonged Intragastric Feeding on Oral Food Intake in Dogs."

[26] Ibid.

McCulloch, the promise of discovering the chemical origins of the mechanism's efficiency that explains why a a multi-year study of blood sugar and carbohydrate metabolism would occur within a Psychiatry Department. If an ingested compound – if *taste* alone, the arrival of a specific molecule to a tissue anticipating its appearance in the mucus linings of the mouth – is capable of higher order regulation of the body's physiology, then a cybernetic, chemical model of the nervous system must be accounted for alongside the electrical one. The nervous system's recognition of the world by the form, the chemical structure, of what composes it, seems somehow primary. Other models, even the electrical model, are but abstractions of this first event of communication – the meeting of an external chemical compound with an organic tissue of the appropriate kind.

IV. Neurotransmitters as requiring a neuroscience of dimension

Neurotransmitters were discovered in 1936 by Henry Hallet Dale with the discovery of the compound, acetylcholine, at work in synapses between neurons of the peripheral nervous system[27]; however, the scientific community did not see Dale's results as conclusive: "although neurotransmitters are now integral to brain science, the controversy between proponents of chemical and electrical transmission continued over a prolonged period." The notion of the firing of a neuron being driven by *chemicals* eluting from a pre-synaptic neuron was rejected on the basis of speed – it was thought the diffusing of molecules via chemical synaptic transmission would be too slow to allow for the seemingly immediate communication between one part of the body and another. As Don Todman describes it, the conflict was over the rejection of the chemical synapse in favor of the electrical synapse: "The prolonged period of debate through the 1940s and much of the 1950s was one of the most significant in the history of neuroscience in the 20th century."[28] McCulloch's intervention in "Dog's Blood-sugar level affected by Taste and Sham-feeding" is not that the chemicals whose work culminate in "taste" function as neurotransmitters. Instead, McCulloch presents experimental evidence that the mere presence of a chemical, a piece of pablum, at the right physiological site, is transiently capable of signaling that *it is as if the esophagus is still in place, it is as if the state is normal, it is as if this response is the correct one*.

Here, in relation to the debate over the means by which the nervous signal is sent (electrical versus chemical), McCulloch's contribution is his chemical compound at the start, at the beginning. The specific chemical compounds here are entrants. This is about how the world enters in and contributes to the chain of signal transmission: not a neurotransmitter built in the body's cells, but an outside molecule we are built to recognize, not a chemical whose role is to communicate between neurons, but a chemical whose role is at the origin. In the esophagostomized dogs, the pablum never reaches the stomach, and yet, by the body's brief demonstration, it seems as if it might. Recall the description of error in digital computing machines in "Of Digital Computers Called Brains" that follows a (1) description of neurosis in human beings and (2) the risks posed by lobotomy as redress for neurosis:

---

[27] Don Todman, "Henry Dale and the discovery of chemical synaptic transmission," *European Neurology* 60:3 (2008): 163.

[28] Todman, 162.

> Every time we build an inverse feedback into a machine, we make it possible for it to have a comparable gremlin, and gremlins are diseases which defy dimensional analysis. Pure numbers and the logarithms of pure numbers are but the stuff of which they are disorders forms.[29]

The "gremlins" are best understood, in the context of the conclusion, as an elevated excitability[30], as the re-generating portion,[31] that is, as the pathological version of the changes that necessarily take place in a set of neurons considered a nervous net over time: "we do not mean that there are no changes in such nervous systems. There must be alterations of excitability of neurons, perhaps of their connections, but as yet, we cannot find them." (376) Gradations of excitability were always anticipated within a set of neurons functioning as an inverse feedback loop; the "gremlin" relates to a change in excitability that, in the digital computer, is unanticipated, and in the human being, causes neurosis.[32] The gremlins are merely the aberrant set of system changes that McCulloch sees as inevitable[33].

Dimensional analysis[34], the conversion of one physical measurement to another (for example – mols per Liter to grams per Liter), proceeds on the basis of analogy, on the basis of the jump from representing the world by one metric to representing the world by another. This is why "pure numbers and the logarithms of pure numbers" (376) are held to be insufficient by McCulloch when addressing neuropathology. The "pure numbers and the logarithms of pure numbers," (376) which paint a function of how electrical activity occurs within the body's central nervous system, are just the things of which (gremlins) are "disorders forms." (376) Gremlins as neuroses are disordered forms of the *formalized*, logarithmic and mathematical representation of the embodied forces of the world, meaning the gremlin is no form at all. This is what "Of Digital Computers Called Brains" brings us back to, the chemical and dimensional nature of tissue, tastebuds, polyps in relation to a dream of taste. If the brute materiality of the chemicals responsible for neuropathology bears no formal model, then this also reveals some possibility that, far from any representational order, there's a chance that neuropathology is affected like taste, with a elemental, chemical origin for the confusion between ingestion and digestion, the confusion between sense and nonsense. The world, without the veil of formalism, at work on itself. This brain is not representational, it is pharmacological. I argue that McCulloch's observations affected his attitude towards potential pharmaceutical, chemical cures

---

[29] McCulloch and Pfeiffer, "Of Digital Computers called Brains," 375.

[30] "There must be alterations of excitability of neurons, perhaps of their connections, but as yet we cannot find them." Ibid., 376.

[31] "We must, while they are alive and active, detect electrically what portions are regenerating." Ibid.

[32] "We know something of the whereabouts of these visas regenerating circuits in two or three mental conditions." Ibid.

[33] McCulloch and Pfeiffer here see error within the nervous system, in the electrical model of the brain, as bound to increase over time because of his conception of the nervous system in physical terms, here, the notion that entropy will work to undo the brain's order: "thus, information is negative entropy." Ibid., 375.

[34] "Every time we build an inverse feedback into a ma- chine we make it possible for it to have a comparable gremlin, and gremlins are diseases which defy dimensional analysis." Ibid., 376.

for neuroses and other forms of neuropathology, and that McCulloch's observations reveal a pantomime nervous system that anticipates future states in the enactment of previous patterns of responding to the world, a world that is also marked, at its point of entry to the body, by its *chemical* structure.

V. Experiments of "Effects of Intraventricular Acetylcholine and Cholinesterase and Related Compounds in Normal and Catatonic cats"

The first identified neurotransmitter was acetylcholine. In "Effects of Intraventricular Acetylcholine and Cholinesterase and Related Compounds in Normal and Catatonic cats," injections of both acetylcholine and the enzyme known for the degradation of acetylcholine[35] were applied to normal and catatonic cats in a series of experiments at the Department of Psychiatry, University of Illinois School of Medicine. The normal cats differed from the catatonic cats because the normal cats were without the lesions induced in the catatonic cats by stereotaxis and electrolysis:

> Six cats were subject to lesions by means of a stereotaxic instrument and electrolysis at a site originally described by Ingram and Ranson and later by Bailey. By slightly modifying this lesion, a syndrome was produced that is indistinguishable from human catatonia; smaller lesions (two cats permitted recovery within ten days to the extent of normal feeding and drinking and response to stimuli from man and other cats; larger lesions were not attended by any significant recovery within ten days.[36]

"Catatonic" was understood as a description of a schizophrenic state. A paper from the time of publication of "Effects of Intraventricular Acetylcholine and Cholinesterase and Related Compounds in Normal and Catatonic cats" describes the onset and periodic nature of catatonia as "a period of erratic conduct followed by an interval of stupor, confusion or excitement, which thereafter undergoes periodic remissions and relapses."[37] It was understood as a flatness, a stupor, a withdrawing disposition periodically present in schizophrenic patients[38]. Another contemporaneous paper further describes catatonia as a retardation, an apathy and a

---

[35] On the understanding of the action of cholinesterases in 1944, see A. Goldstein, "The Mechanism of Enzyme-Inhibitor-Substrate Reactions: Illustrated by the Cholinesterase-Physostigmine-Acetylcholine System." *Journal of General Physiology*. 27:6 (1944): 529–580.

[36] Warren McCulloch, Ellen Ridley and Stephen Sherwood, "Effects of Intraventricular Acetylcholine and Cholinesterase and Related Compounds in Normal and Catatonic cats" (1951), Warren S. McCulloch Papers, Box 60. Mss.B.M139.

[37] J. S. Bonar Lindsay, "Periodic Catatonia." *Journal of Mental Science* 94:396 (1948): 590.

[38] "The periodicity is remarkable in the rapidity with which all changes occur. In the periods of remission the patient is free of catatonia and associated symptom-complex (sympatheticotonia), but is still dull, apathetic and withdrawn; he often recalls events from the reactive phase, but without insight. The patient is still schizophrenic, with emotional flattening and poverty of ideation, and remains so throughout. In the reactive phase the picture is one of catatonic stupor or excitement, with clinical evidence of sympathetic over-activity." Ibid.

fatiguability[39]. The specific hypothesis of the research published in the paper "Effects of Intraventricular Acetylcholine and Cholinesterase and Related Compounds in Normal and Catatonic cats," is that the enzyme, cholinesterase, "should reduce the symptoms of schizophrenia"[40]:

> It has been known for some time that di-iso-fluorophosphonate and similar drugs which are *anti-cholinesterase* in nature, in toxic doses, produce syndromes resembling certain psychoses, and that, in schizophrenics they aggravate the signs and symptoms. Conversely, it was thought that cholinesterase and other drugs counteracting acetylcholine should reduce the manifestations of schizophrenia…"[41]

It was an experiment in pharmacology: an assessment of whether certain compounds – a neurotransmitter and a protein known to destroy neurotransmitters – had the potential to interact with the nervous system and produce differing effects in normal cats and in cats whose condition resembles that of human schizophrenic patient. It was an experiment in the susceptibility of the nervous system, not to electricity, but to the presence or absence of matter of a certain kind; molecules of a certain structure, polarity and composition. The digital is even here, in the bipolar metric of presence and absence. Before the "all-or-none signal," there is an all-or-none presence, an achievement in the way of a concentration above the threshold for normal nervous activity. As for the results from the injections in normal and catatonic cats at intraventricular sites in each:

(A) over a duration of two hours following injection, the six catatonic cats receiving acetylcholine demonstrated "a return or exaggeration of all 'catatonic' signs for two hours,"[42] and the catatonic cats receiving cholinesterase demonstrated a transient remission of catatonic signs (further, McCulloch et al. note how in these cats, after many injections of cholinesterase were applied, the catatonic cats' remission was "sustained and advanced."[43])
(B) while the four cats without lesions, when injected with acetylcholine: "exhibited agitation and behavior which might be interpreted as hallucinatory, or they seemed to be preoccupied

---

[39] Helen Kitzinger, Devere G. Arnold, Robert W. Cartwright & David Shapiro, "A Preliminary Study of the Effects of Glutamic Acid on Catatonic Schizophrenics," *Rorschach Research Exchange and Journal of Projective Techniques* 13:2 (1949): 210-218.

[40] "It has been known for some time that di-iso-fluorophosphonate and similar drugs which are *anti-cholinesterase* in nature, in toxic doses, produce syndromes resembling certain psychoses, and that, in schizophrenics they aggravate the signs and symptoms. Conversely, it was thought that cholinesterase and other drugs counteracting acetylcholine should reduce the manifestations of schizophrenia, and they have done so, on injection into the cerebral ventricles of man.…" McCulloch, Ridley and Sherwood. "Effects of Intraventricular Acetylcholine and Cholinesterase and Related Compounds in Normal and Catatonic Cats."

[41] My emphasis; ibid.

[42] Ibid.

[43] Ibid.

> with their internal state, showing anger or fear in response to stimuli not perceived by observers."[44]

The model of the brain emerges from these results. The cholinesterase causes a remission of symptoms in the catatonic cats and the acetylcholine causes an exaggeration of symptoms in the catatonic cats as well as hallucinations and agitation[45] in the "normal" cats – this is a pharmacological model. I argue that the notion underlying these conclusions and motivating these experiments is a notion of *cure* sustained by specific biochemical standards for normal and abnormal. The central nervous system is susceptible,[46] sensitive to the chemical composition of an internal environment. As we see in the paper's introduction: "Cannon and Rosenblueth's thesis [is] that in the peripheral nervous system, the deafferented part becomes oversensitized to stimuli may obtain also for the central nervous system."[47] The stimuli referred to are eserine, atropine and hyoscine, which bear forth particular changes in patients with Parkinson's as described by the authors: "eserine aggravates Parkinsonism in Parkinsonian man and monkeys with lesions between the nucleus ruber and the substantia nigra; whereas atropine, hyoscine and similar compounds decrease symptoms."[48] To be clear, the framing of the paper in the terms of these chemical compounds' effect on neurological disease, does not represent a departure from the electrical model of the central nervous system. It's a complication, an embedment. It speaks of a relation of the central nervous system not only to *matter,* in the form of chemicals atropine hyoscine acetylcholine cholinesterase, but also to *health*. Electricity is not separate from this conceptualization — in fact the physicality of an electrical change is emphasized by it.

The emergence of a notion of cure takes place at skin, in an external world coming to shape an internal one, where the laws governing physical and chemical activity are the same. The assurance that gives faith to a medical intervention is here not *penetration;* the intraventricular injection of acetylcholine and cholinesterase does not bring to the brain something it does not already have.[49] Instead, it is the *consistency of the laws* across the cutaneous boundary. If the legitimacy of a curative medical intervention rests on the potential, the plausibility of a therapy to attain a physical future that differs from the present, then what secures that potential is the "science" that makes plain the curative power of the therapy being applied. Here, I argue that that "science" comes in the form of natural law, where the laws governing matter responsible for

---

[44] Ibid.

[45] "They exhibited agitation and a behavior which might be interpreted as hallucinatory, or they seemed to be preoccupied with their internal state, showing anger or fear in response to stimuli not perceived by observers; they also salivated profusely and defecated within a few moments after the injection." Ibid.

[46] "Eserine aggravates Parkinsonism in Parkinsonian man and in monkeys with lesions between the nucleus ruber and substantia nigra, whereas atropine, hyoscine and similar compounds decrease symptoms. Cannon and Rosenblueth's thesis that in the peripheral nervous system the deafferented part becomes oversensitized to stimuli may obtain also for the central nervous system-as was suggested originally by Dale and by Lettvin the case of Parkinsonism." Ibid.

[47] Ibid.

[48] Ibid.

[49] Acetylcholine and CHE exist in the body in substantial amounts.

mentation, schizophrenic or otherwise, are the same as those of the world. The body is not a world unto itself, but a *boundary belonging to the world*.[50] This recognition that the body's internal environment is only separate from an external one due to the boundary of the skin, which an injection quickly renders friable, and not due to the laws of its activity explains the assumption of curative intervention in McCulloch and collaborators' research. In "Effects of Intraventricular Acetylcholine and Cholinesterase and related compounds in normal and catatonic cats," the implicit cure is a pharmacological one. The promise of chemicals once external to the body taking effect inside of it itself becomes a conceptual method. McCulloch and collaborators see a human treated with Pilocarpine where there is only a hallucinatory cat: "as the affect of the drug (acetylcholine) wore off, they resembled markedly a man who has been given a dose of pilocarpine."[51] McCulloch's animal experiments can therefore be considered early experiments in the *pharmacology of neuropathology*, applying compounds and observing their effect on neurological function.

VI. Ridley's synthesis of cholinesterase as a drug

Concepts of natural law, cure and intervention emerge from the paper but they also emerge from the work of those who collaborated with McCulloch on this paper, for example in the work of Ellen Ridley in the artificial synthesis of cholinesterase in relation to Manteno State Hospital in Manteno, Illinois and Stephen L. Sherwood in the prefrontal lobotomies performed at Severalls Hospital in Colchester England[52]. Medical intervention in instances of neuroses or other instances of diagnosed neuropathology, must be analyzed in relation to McCulloch's research on the nervous system because intervention, whether through surgery or pharmacology can be understood as the physical or chemical enactment of recognition — the surgical work on the body or the injection of chemical therapies occur on the basis that the laws facilitating the disease-state, can be employed to attempt to reverse the progression of disease or internal injury, as "the inside and outside of the body are spaces where the materialistic laws of science and medicine obtain equally."[53] Accordingly, McCulloch's research can be understood as participating in the tradition of medical materialism, even if his emphasis on the nervous

---

[50] See McCulloch and Brodey on the phospholipid bilayer in "Biological Sciences": "Since the micelles we are most concerned with in animals, and above all in their nervous systems, are in large measure composed primarily of lipids, notably phospholipids, we should picture them carefully. Phospholipids are amphiphilic. They lower the gradient between water and air and accumulate there, with their polar heads burrowing among the flickering cages of water and their slippery paraffin tails writhing freely among each other. The present guess is that the bonds of the head to water endure some 10^-7 sec. 10^-8 or sec., which is a thousand times longer." (302). "Ca+ + ion is necessary to the integrity of the membrane. Ca++ is displaced locally, say by an electromotive force, local disordering occurs, and the resistance falls locally. Na+ with its water shell then rushes in, and later K+ leaks out." (317) The membranes are leaky by design.

[51] McCulloch, Ridley and Sherwood. "Effects of Intraventricular Acetylcholine and Cholinesterase and Related Compounds in Normal and Catatonic cats."

[52] I will elaborate on Dr. Sherwood's work in the Conclusion. McCulloch was in possession of a number of files from Sherwood's lobotomy patients at the time of his death.

[53] Gaetan Micco, personal communication.

system's capacity to build and respond to a perceptual and chemical world renders this a less neat categorization. Neurological, medical materialism, a tradition to which McCulloch's work is indebted, was not without its critics. William James' critique of medical materialism, in *Varieties of Religious Experience*, not only juxtaposes medical materialism with mysticism but sees attention to the structure underlying behavior as resulting in something lost. From his published lecture, "Religion and Neurology":

> Medical materialism seems indeed a good appellation for the too simple-minded system of thought which we are considering. Medical materialism finishes up Saint Paul by calling his vision on the road to Damascus a discharging lesion of the occipital cortex, he being an epileptic. It snuffs out Saint Teresa as an hysteric, Saint Francis of Assisi as an hereditary degenerate. George Fox's discontent with the shams of his age, and his pining for spiritual veracity, it treats as a symptom of a disordered colon. Carlyle's organ-tones of misery it accounts for by a gastro-duodenal catarrh. All such mental over-tensions, it says, are, when you come to the bottom of the matter, mere affairs of diathesis (auto-intoxications most probably), due to the perverted action of various glands which physiology will yet discover.[54]

In my view, McCulloch's conception of the electrical and chemical nervous system do not conform with those of medical materialism as his inquiry is less oriented towards a 'finishing up' of Saint Paul and more towards mapping the chemical and physical structures that afforded the world entry, and that afforded Paul a response to the world that changed it. There is still mystery, here, and wonder in the attention to the exchange that occurs between the world and the nervous system.

The archive at American Philosophical Society contain documentation of several interactions of McCulloch with biochemist Ellen Ridley or documentation of conversations with others regarding her scholarship. The first is a typewritten note from June 22, 1951, which describes the interactions of Dr. A.C. Ivey, Vice President of the University of Illinois College of Medicine, and McCulloch with an editor of the journal *Proceedings of the Society for Experimental Biology and Medicine,* in which "Effects of Intraventricular Acetylcholine and Cholinesterase and Related Compounds in Normal and Catatonic cats," was published. The note details Ivey's and McCulloch's joint response to the idea that Ridley only be listed as "technical assistant" and not as an author. The note details how McCulloch consulted with Dr. Ivey who believed that Ridley's name be included on the basis that "authorship is anyone who has done any of the work."[55] The note also details how McCulloch consulted with an additional physician, Dr. Carmichael. About this second meeting, the note says: "it was their understanding that it stay as it was originally written,"[56] with Ellen Ridley's name included as an author of the piece.

I refer to this back-and-forth exchange over Ridley's diminution to call attention to her importance and role in pharmacological *discovery* — not only with regard to the experiment with

---

[54] William James, *The Varieties Of Religious Experience: A Study In Human Nature* (1902) (New York: Modern Library, 1936), 14

[55] Typewritten note accompanying draft of "Effects of Intraventricular Acetylcholine and Cholinesterase and Related Compounds in Normal and Catatonic Cats." (1951)

[56] Ibid.

acetylcholine and cholinesterase but with regard to her sustained effort in what she described as the "carbohydrate problem."[57]

Ridley dispatched a typewritten letter to McCulloch shortly after his departure from the University of Illinois School of Medicine, where she describes how she and a collaborator, "Jack", successfully purified and isolated cholinesterase from human beings. Cholinesterase is an enzyme, that when preserved in its active form, removes acetylcholine from the neural synapse.

> No doubt you are a bit curious about the state of things here. Jack with my meager help succeeded in making another batch of human ChE. We ran just one biological assay to check its potency and were happy with the results, but then we both lost the roof over our heads. Fortunately, the stuff was at a stage where it could be safely deep-frozen and kept, so wi [sic] will have to admit that it is still at the university as a friend of Jack's is keeping it, but I doubt if others realize that.[58]

This is essentially moonshine cholinesterase (ChE) kept without the University's sanction in a freezer within Department of Psychiatry at the University of Illinois School of Medicine. The origin of the ChE samples is unclear but she is forthright with their purpose: "We would want to run further tests on it before injecting patients, but we know we have a logical, repeatable way of producing the stuff we want."[59] After an initial biological assay, more tests are needed before injecting patients.

Ridley's research constitutes a new phase of the work begun with "Effects of Intraventricular Acetylcholine and cholinesterase and related compounds in normal and catatonic cats" (1951). Whereas before, the research goal appeared to be tracking the behavior of a cat upon receiving an injection of acetylcholine – to observe the cat's presentation as catatonic or not. Now, the research goal appears to be the curing of the organism, developing a related compound to cultivate a specific behavior. Ridley's correspondence reaches its material end in the nervous tissues of schizophrenic patients, but there are other, administrative goals for the letter. For the sufficient production of cholinesterase as a drug, Ridley requires a lab, a pharmaceutical company to take over the project of isolating human ChE, and a patent - all of which require money and influence.

> Neither Jack nor I have a lab suitable for the preparation of ChE at the moment, neither of us are doing what we really would like to be, but trying to make sensible plans for the future. Ted is still plugging away at Manteno, but we dare not to use the esterase on the patients without further testing. As you know, there is always the chance that the government will decide that they need the stuff even if we could make some. We can only think of two ways of putting the stuff into sufficient production to continue (1) that some mysterious angel should for no apparent reason appear and grant us a lab or (2) that we should persuade a drug house to take it over.[60]

---

[57] Ellen Ridley. Letter to Warren S. McCulloch (1952), Warren S. McCulloch Papers, Box 60. Mss.B.M139.

[58] Ibid.

[59] Ibid.

[60] Ibid.

There is a need for further testing, a chance that the government could manufacture ChE and outpace the progress made by Ridley and her collaborator. There is the need of a physical laboratory or else the need of a drug house to purchase the rights to manufacture the cholinesterase. There is no elaboration on what is meant by the "government"; however, Ridley notes that she hesitates to be divested of the rights to ChE because she would then be divested of the ability to direct its use:

> The difficulty with the second (in reference to the passage above, the second option is that of having a drug company take over the project) is that we have no jurisdiction over the use of the drug should it be done this way. Heads of drug houses change - the product remains in production, but gentlemen's agreements are forgotten…and then to be very practical, Jack and I really want to keep our hands in the pie and Ted does want the stuff to work with.[61]

Ridley writes of Ted who "really wants the stuff to work with,"[62] a reference to a collaborator employed at Manteno State Hospital, a state-run psychiatric hospital in Manteno, Illinois, a hospital that, at it most active, had over 8,000 resident patients.[63] In the 1950s, Manteno state hospital was "the 4th largest in the nation"[64]. Manteno State Hospital is now burned to the ground in its entirety. In 1939, close to 400 patients and staff contracted typhoid fever and modern accounts of the ruins of the former asylum, laid out in a "cottage plan" where "patients were housed in a series of separate buildings rather than one single institution" (56), discuss hearing ghostly ricochets of a hospital PA system and witnessing the specters of doctors and nurses[65].

The explicit writing motive of Ridley's letter is to secure an introduction to Castor Ooms, to pursue whether Ooms might fund the lab for large-scale production of cholinesterase. Additional information about the figure, Ooms is not offered in the letter, and not available at the time of filing. Ridley requests that McCulloch send to Ooms the following text:

> "In my opinion, this discovery is of great promise, and if the promise is realized, it will certainly play an important part in serving the mental health problem of the world…in addition to the military value (Brain Feb. 1952). The work to date has been done *under my suggestion* by Jack Snider and Ellen Ridley and I authorize them to proceed in any

---

[61] Ibid.

[62] Ibid.

[63] Asylum Projects. "Manteno State Hospital." May 22, 2020. Accessed Dec. 3, 2020. <https://www.asylumprojects.org/index.php/Manteno_State_Hospital>.

[64] Ibid.

[65] "Since the hospital's closure, many people have visited its remains and have come away with strange stories. They have seen apparitions of patients and nurses, and have heard voices over the long-defunct intercom." Ibid.

> way they deam [sic] wise to do it. Anything that you can do for them or suggestions you can make will be greatly appreciated."[66]

Ridley justifies the ask to McCulloch because she claims that it will permit her to "keep plugging away at the carbohydrate problem"[67] as "the goal hasn't changed"[68]. From the requested introduction to Ooms, the requested text of that introduction, and the manner in which the request is framed - *the goal hasn't changed*[69] - one can concur that the goal was shared — that the carbohydrate problem, as experimentally investigated in "Dog's Blood-sugar level affected by Taste and Sham-feeding", was a priority to McCulloch *and* Ridley. The "carbohydrate problem" linked chemical stimuli to nervous activity as discussed in "Aviation in Medicine" as what secures[70] the voltage necessary for the transmission of the nervous impulse. The formation of ions through oxidative metabolism are exchanged along the membrane, "building up EMF", building up of the voltage, via the concentration of sugar derivatives:

> Sugar is brought anorobically [sic] to the level of pyruvic acid. From there on, many of the steps are oxidative and among these are those which are crucial in building up the EMF at the membrane. Sugar and oxygen enter the cell in an unionized form. Within the cell, in the later stages of oxidative metabolism, ions are formed, equal in number, opposite in sign, but differing vastly in their size and hence in the velocity with which they travel under a given gradient of pressure due to constant production. Proceeding through the membrane, which reduces the velocity of both, the smaller are less retarded. Thus, as in any concentration cell, there appears a difference of voltage between the outside and in the inside of the cell membrane.[71]

The metabolites of carbohydrate oxidation are charged unlike the sugar itself. The metabolites, "due to constant production" accrue "under a given gradient of pressure" and then proceed through the membrane differentially, allowing the membrane to attain a charge. Such thinking, in relation to the membrane, grounds McCulloch's statement in "Automata of Man - MESM unveiled" that what registers on the encephalogram is *chemo-electric*:

---

[66] Emphasis my own. Ridley, Letter to Warren S. McCulloch, 1952.

[67] Ibid.

[68] Ibid.

[69] "Warren, will you please consider this carefully. I think that we can manage to keep plugging away at the carbohydrate problem, even if I do have to take the long way round, and make money for a while…the goal hasn't changed." Ibid.

[70] "In the general range of values which a civilian aviator might reach flying on an empty stomach, the excitability of the cells of his nervous system my be thought of as roughly proportional to the product of his blood sugar by the saturation of his hemoglobin with oxygen provided no other item, above all his circulation, is significantly altered." Warren S. McCulloch, "Aviation in Medicine" (1945), Warren S. McCulloch Papers, Box 58. Mss.B.M139.

[71] Ibid.

> … while all of these rhythms – including the brain ‘waves’ appearing on the surface of the cortex, as found in electro-encephalography, as well as with the active aperiodic pulses and trains of pulse-like potentials associated with nervous paths, are quite subtle and often neglected in considering the large scale and long time integrative action of the system, they are always present. They are chemo-electric.[72]

Brain rhythms are chemo-electric, and while not being the “communications language of the system”[73], not being the means by which one neuron communicates to the next, brain rhythms are the “buzz” demonstrating “that the system is in flux.”[74] And this is separate from information but is a hallmark of life : “their [the rhythms’] buzz is not the information flux, only that the system *is* dynamically in flux”[75]. Marked from information, the chemical contributions to the brain’s activity, which reaches its summation in the rhythms like brain waves reveals a brain that is ‘running’ even if considered mere noise: “once can tell that a complex biological ‘factory’ is running by its mere dissipative noise”[76]. It is difficult to distinguish how speaking of such rhythms is different than speaking of the cardiac rhythm, where what is described as ‘noise’ is merely the heartbeat of the brain, communicative of nothing but the persistence of life.

In one section of the letter, Ridley remarked on the fact that she and a collaborator had discovered “a logical repeatable way of producing the stuff [they] want”[77] and in part of the letter cited above, Ridley remarks that “Ted does want the stuff to work with”[78] – this is a pharmacological method in pursuit of pharmacological ends. It is a neurophysiology of the drug. The method spoken to in Ridley’s letter (logical, repeatable) and the ends (the bodies of the patients at Manteno state hospital for the assumed intraventricular injections of ChE) reveal an interventionist model of neurophysiological research that requires a chemical understanding of the nervous system.

VII. Pharmacology and Homeostasis

---

[72] Warren S. McCulloch, “Automata Model of Man - MESM unveiled,” (1967) Warren S. McCulloch Papers, Box 58. Mss.B.M139.

[73] Ibid.

[74] Ibid.

[75] Emphasis my own. Ibid.

[76] Ibid.

[77] Ridley, Letter to McCulloch, 1952.

[78] Ibid.

McCulloch builds upon ideas of homeostasis in the philosophy of biology to argue that the operation of homeostatic systems can be modified[79] by chemical agents in an argument that splices traditional ideas of homeostasis with ideas of pharmacology:

> It is clear that, in physiology, Bernard-Sechenov-Cannon's concept of homeostatic regulation of the watery internal milieu is invoked as a guiding principle, but there has been no way to relate it to the brain and behavior. This obviously was impossible to realize if one was limited to static and linearly approximate approaches to equilibria. The concept of 'homeokinesis' of dynamic regulation through mediation of non-linear oscillators - engine cycles or motor actuating chains in simple language - offers a foundation.[80]

There are two references here, one to the concept of homeostatic regulation developed in different ways by Claude Bernard, Ivan Sechenov and Walter Cannon, and the other to McCulloch's own concept of "homeokinesis." In a 1929 paper, Cannon described homeostasis in the following way:

> The present discussion is concerned with the physiological rather than physical arrangements for attaining constancy. The coordinated physiological reactions which maintain most of the steady states in the body are so complex, and are so peculiar to the living organism, that it has been suggested (Cannon, 1926) that a specific designation for these states be employed—homeostasis.[81]

As an adjustment to Cannon's theory of the maintenance of the body's steady-states, McCulloch proposes *homeokinesis*, an reinterpretation of the concept of homeostasis able to accommodate the non-linear, oscillatory qualities identified by McCulloch in the body's internal systems[82]:

> The scheme of regulation and control by which these oscillator systems are mediated to their non-linear stable operating points is best described by the term 'homeokinesis,' as a modification of Cannon's concept of homeostasis, using it to connote that it is the manipulation of kinetic variables of space and time by which the processes, predominantly regulatory, take place.[83]

---

[79] "The orbital weaving of 'satisfying paths' through two handfuls of primary oscillator chains into operative patterns becomes the form of the driving brain's algorism [sic] Such a system is operational, it can be built, it can be modified in how it runs." McCulloch, "Automata Model of Man - MESM unveiled."

[80] Ibid.

[81] Walter B Cannon, "Organization for physiological homeostasis." *Physiological Review*. 9 (1929): 399-431.

[82] "What seems to be common among all the internal systems is that their actions are organized into essentially unstable closed chains of a biochemical-mechanical-electrical nature involving the solids, liquids and gases in the body." McCulloch, "Automata Model of Man - MESM unveiled."

[83] Ibid.

McCulloch's *homeokinesis,* contrary to Cannon's homeostasis, can describe the relationship between the brain and behavior *because* it subsumes aspects of environment as variables in an organism's regulation. The variables of space and time are taken into consideration by the term, *homeokinesis,* and the organisms's space and time is held to be manipulable by drugs. McCulloch writes on the relationship of drugs to the steady state achieved by the process of homeokinesis that "one way that is 'obviously' known to modify it [the system] is by chemical concentration of pharmacological agents - drugs."[84] Space and time are kinetic variables, the values of which change as an organism *as a system* eludes or adheres to threshold values for certain variables. I argue that temperature, pH, blood salinity, glucose levels, would also be comprised in estimations of space, thinking in terms of concentration, or time, thinking in terms of metabolic rates. The explicit linking of a homeostatic system and pharmacological change - "it can be modified in how it runs" is what compels a broadening of the understanding of the cybernetics movement to include a medical, clinical cybernetics. In the same breath, McCulloch writes of the side effects possible when drugs enter a homeokinetic system: "It is no surprise, with present knowledge, that a drug affects one chain interacts with others. It has 'side effects.'Some day more specific control may be known."[85] Drugs are how to influence the physical-chemical-mechanical-hydraulic chains[86] that McCulloch perceives to be at work in the brain as a homeokinetic system.

To compare this pharmacological, homeokinetic brain with the electrical brain discussed in Chapter 1: time is the central variable which, in the Logical Calculus, is deemed capable of describing the activity of neurons in an open system.[87] The addition of homeokinesis is the variable, space, understood less as location than as dimension. Space and time are can be understood to be of import because in a non-linear, oscillating system they are the only data of the internal system capable of representing a process of chaining and unchaining and chaining to a world. And it is the legibility of the *unchaining* in particular, the departure from steady state values, as registered in the kinetic variables of space and time, that reveals the organism's status as belonging to a world. In the departure from the range of values that ensure the organism's continuity, there is a dual awareness – an awareness of being thrown, in the Heideggerian

---

[84] Ibid.

[85] Ibid.

[86] "However, in similar fashion, as the nature of the physical-chemical-mechanical-hydraulic chains become better known, the possibility of influencing them by various means - <u>including the ends that have been desired for psa</u> - can grow." Ibid.

[87] "In its own domain the difference between equivalent nets and nets equivalent in the narrow sense indicates the appropriate use and importance of temporal studies of nervous activity: and to mathematical biophysics the theory contributes a tool for rigorous symbolic treatment of known nets and an easy method of constructing hypothetical nets of required properties." McCulloch and Pitts, "A Logical Calculus," 360.

sense,[88] and of throwing back, as Rilke would say.[89] McCulloch's homeokinetic, pharmacological brain is conceptually distinct from Heidegger's *Dasein*; however, the language of thrownness as a characteristic of the Dasein's Being, in which *Dasein* is "there" only inasmuch as "it finds itself in its thrownness," is not irrelevant to McCulloch's own inquiries.[90] Heidegger writes in terms of states-of-mind. Thrownness is not a physical delivery to oneself but an unintentional thought, a stumbling upon oneself as *in time* and in a world of "facticity." I include him to help consider how existence betwixt a range of values can give a being a *world* in this Heideggerian sense of the term. In the case of McCulloch, we have a brain delivered to certain variables of space such as the concentration of blood sugar or ChE and certain variables of time, such as metabolic rates, that can result from the use of a drug. The drug becomes the environment and the world follows.

"Automata of man. MESM unveiled" was written in 1967, near the end of McCulloch's life, as a draft of the paper later renamed "Behavioral Model of Man: His Chains Revealed." In the draft, the nervous system is seemingly exchanged for any internal physiological system as the object of study. McCulloch seeks a more general principle of physiological organization. The question is what is *common* among all internal systems. He writes:

> What seems to be common among all the internal systems is that their actions are organized into essentially unstable closed chains of a biochemical-mechanical-electrical

---

[88] "Being-in-the-world a Being which has been thrown and submitted to the 'world.'" Martin Heidegger, *Being and Time,* trans. John Macquarrie and Edward Robinson (New York: Harper, 2008), 204.

[89] "As long as you catch what you've thrown yourself, it's all
just clever agility and venial gain;
but when you suddenly come to catch a ball
an eternal playmate has thrown
at you, at your center, has exactly set
in mastered motion, in an arc
out of God's great bridge-building -
then that you can catch is real power:
not yours, the world's. And when you even
have the strength to throw it back,
no, better yet: have forgotten courage and strength
and thrown it back already...(the way the year
throws birds, the flocks of migrating birds
hurled over the ocean from an old to a new
warmth -) then, that gamble, is the first moment
you too can be said to play."
Rainer Maria Rilke, "The Tao that can be Named," in *The Inner Sky: Poems, Notes, Dreams by Rainer Maria Rilke,* ed. David R. Godine, tr. Damion Searls (Np, David R. Godine Publisher, 2010).

[90] "This characteristic of Dasein's Being - this 'that it is' is veiled in its 'whence' and 'whither', yet disclosed in itself all the more unveiledly; we call it the 'thrownness' of this entity into its 'there'; indeed, it is thrown in such a way that, as Being-in-the-world, it is the 'there'." (174) Heidegger, Martin. *Being and Time*. Trans. John Macquarrie and Edward Robinson. Harper Perennial Modern Thought, 2008.

> nature involving the solids, liquids and gases in the body. They usually end as stable, non-linear limit cycles, often passing through transient stages as the organism is affected by life's contingencies…the collection of all of these chains form an extensive system of non-linear oscillators whose action is controlled mainly by inhibition.[91]

Homeokinesis aims to explain regulatory *inhibitory* activity of internal systems whose activity is oscillating and non-linear. Though the enzyme itself is not mentioned, one example of inhibitory activity is the degradative effect of ChE, cholinesterase, at the synapse. ChE chemically alters the neurotransmitter, acetylcholine, and ChE, in the experiments published in "Effects of Intraventricular Acetylcholine and cholinesterase and related compounds in normal and catatonic cats," was observed to reduce catatonic symptoms in cats whose condition would otherwise be comparable human schizophrenia.

McCulloch demarcates *homeokinesis* from traditional theories of self-regulation, which are interpreted as incapable of linking the brain to behavior. "It is clear that, in physiology, Bernard-Sechenov-Cannon's concept of homeostatic regulation of the watery internal milieu is invoked as a guiding principle, but there has been no way to relate it to the brain and behavior."[92] McCulloch marks the influence of Claude Bernard's theory of the internal milieu on both Ivan Secehenov's and Walter Cannon's theories of the organism's ability to self-regulate. Cannon describes Bernard's account of blood and lymph as the physical constituents of the milieu interieur, "made and controlled by the organism itself"[93] and cites Bernard's *Les phenomènes de la vie* in "Organization for Physiological Homeostasis": "It is the fixity of the 'milieu interieur' which is the condition of free and independent life," (400) and "all the vital mechanisms, however varied they may be, have only one object, that of preserving constant the conditions of life in the internal environment." (400) Cannon interprets this fixity and constancy of the milieu interior as necessary to Bernard's concept of freedom, where "organisms become more independent from the outside world" (400) by "preserving uniform their own inner world in spite of shifts of outer circumstances." (400) And McCulloch's departure? The mingling of the world and the milieu via the kinetics, the variables of time and space that position the organism within surroundings of a certain kind and drugs, which come from the outside and integrate within the fluid matrix, reminding the brain of its own activity. McCulloch elaborates on homeostasis and pharmacology:

> The orbital weaving of 'satisfying' paths through two handfuls of primary oscillator chains into operative patterns becomes the form of the driving brain's algorithms. Such a system is operational, it can be built, it can be modified in how it runs. In fact one way that is 'obviously' known to modify it is by chemical concentrations of pharmacological agents - drugs. (the intent is not to impress the reader with brilliant novelty, but to bring all parts of a clear, simple, reasonable picture together into coherence and consistency.)[94]

---

[91] McCulloch, "Automata Model of Man - MESM unveiled."

[92] Ibid.

[93] Cannon, "Organization for physiological homeostasis," 400.

[94] McCulloch,"Automata Model of Man - MESM unveiled."

The system being referred to in “such a system is operational”[95] is the nervous system as one of many physiological, internal systems, “often passing through transient stages as the organism is affected by life’s contingencies”[96]

The brain’s activity is patterned, algorithmic and attains a form non-unique to the nervous system: the “orbital weaving of ‘satisfying paths’ through two handfuls of primary oscillator chains”[97]. An orbital refers to the site of electrons, “regions of space with different probabilities of having an electron.”[98] An oscillator chain refers to a metabolic pathway of one of two states. From a 1950 article on non-linear oscillating systems by J. S. Schaffner we read:

> Most important for the study of an oscillatory system are the steady- state oscillations. They may be stable or unstable, depending on whether the oscillator will or will not return to its original state after being subjected to a small disturbance (noise, etc.). An oscillator may have several possible steady-state oscillations.[99]

In addition, an oscillator is specific type of *circuit*, one that generates a signal in perpetuity without requiring inputs from an external source, an electrical version of the pendulum’s swings.[100] McCulloch continues, writing of drugs’ effects:

> Drugs’ are known to induce sleep, hunger, its lack, sexual interest, its lack, voiding, its prevention, more recently release of anxiety, heightening of tension, etc. (The use of alcohol and nicotine is so common that it may be overlooked.)[101]

---

95 Ibid.

96 Ibid.

97 Ibid.

98 LibreTexts. “1.2: Atomic Structure - Orbitals”. *Chemistry*. October 15 2020. Accessed Dec. 3 2020 < https://chem.libretexts.org/Bookshelves/Organic_Chemistry/Map%3A_Organic_Chemistry_(McMurry)/01%3A_Structure_and_Bonding/1.03%3A_Atomic_Structure_-_Orbitals>.

99 J. S. Schaffner, “Almost Sinusoidal oscillations in non-linear systems.” University of Illinois Engineering Experiment Station. Bulletin Series No. 421 (1950). University of Illinois at Urbana-Champaign Library. Accessed Dec 3 2020 <https://www.ideals.illinois.edu/bitstream/handle/2142/4369/engineeringexperv00000i00421.pdf?sequence=3&isAllowed=y>.

100 “The problem of designing a low frequency electronic timebase of reasonable size and cost which will maintain timing accuracy over the military temperature range has plagued circuit designers for quite some time. On the other hand, mechanical oscillators such as pendulums and balance wheels have a reputation for excellent low frequency timekeeping but provide no electronic output and require energy to sustain their oscillation.” U.S. Army, Harry Diamond Laboratories. “Proceedings of the Timers for Ordnance Symposium, Volume 2.” U.S. Army Materiel Command, 1966.

101 McCulloch, “Automata Model of Man - MESM unveiled.”

This is a *control* apart from an electrical origin. Though chains connote established routes of metabolic activity, what affects them, what *controls* them and even causes them to influence each other, is the introduction of a material recognized as their own. The homeokinetic, pharmacological brain consists of an internal system controlled by variables corresponding to the organ's environment that catch up certain values. Like the electrical model of the brain, the homeokinetic, pharmacological brain requires the notion of the threshold value, over which or under which certain changes will be induced in the system in a deviation from a steady-state. The electrical model's chief variable was *time*.

Here, we have a dimensional world, a brain in the body, where space, which I take to be values corresponding to the organism's environment – blood glucose levels, pablum, ChE and acetylcholine – works with the variable, time to originate a world at the moment when the world's molecules, as drugs, enter the body. In the following chapter, I will discuss a new object, the "biological computer," which is not a brain, but rather a *reproductive molecule*. I will analyze further how McCulloch conceptualized the organism's environment, because, as we will see, notions of "world" and the possibility of extra-terrestrial beings informed how McCulloch defined itself. McCulloch considered the life-question at both the level of ecology and the level of the molecule. In addition to the proteins he considers the origin for evolution, the "biological computers," there are water molecules, which in the configuration by which they add and subtract from each other carry information, in a molecular conception of information that, in opposition to the genetic conception of information, privileges form over the program.

Chapter 3: The environment at the origin of life

In McCulloch's transformation of the concept of homeostasis to account for time, space and drug-brain interactions, we were brought up against the contingency of living systems. *Homeokinesis* posits a chemical regulator for the brain's activity — and in so doing, a physical, structural apparatus for the relay of information essential for life. McCulloch's pharmacological brain is not a departure from the electrical model he submits with Pfeiffer in "Of Digital Computers Called Brains," rather it is an implantation of the electrical model in a body, in a living system approximated by the cats and dogs on which he experimented. Not only do Ridley's conversations with McCulloch regarding the "carbohydrate problem" with reference to neuropathology and a potential cholinesterase therapy embed the device, the brain, in the workings of matter, they also embed the device in human life. McCulloch's medical cybernetics requires an evaluation of the brain as both device and organ, both technical and living, and this chapter concerns what underlies the brain's activity on a molecular scale, accounting for McCulloch's response to the question, *What is life?*

I will focus on four papers – "Biological Computers" (1957-1958)[102], "Biological Sciences" (1966), "Automata model of man - MESM unveiled" (1967), and "Aviation in Medicine" (1945) – to discern how McCulloch's origin story relies on differs from the origin story supplied by Watson and Crick, where the hereditary material of living systems is Deoxyribose Nucleic Acid (DNA). McCulloch posits instead a molecular 'biological computer' that, in its particular chemical and enzymatic structure, serves as both cause for and substance of evolution. This 'biological computer' is not a brain but a molecule, which carries in its structure the results of a million past yes-or-no decisions due to how a given facet of its structure permitted an efficient catalysis of a reaction or not. If the reproductive molecule, the 'biological computer,'did not carry out the reactions with which it was charged, it would obsolesce, and another molecule would supplant it. Because the molecules produce themselves as well as other molecules of greater complexity, future generations of molecules do not bear the shape of a molecule conducting reactions less efficiently and instead bear the shape of the molecule the supplants it. In comparison to the scale of the living system of the previous chapter, we are now at the level of the molecule, addressing the substrate underlying nervous activity.

I argue that McCulloch presents a model of heredity that opened up a field of study that was foreclosed by the genetic revolution, a field organized around the question: how do we study an object that is physical but not technical? Instead of merely applying technological analogies to biological objects, McCulloch attempts to devise a method for how to understand biological objects as capable of carrying information while also being *alive*. In this way, acknowledging the information and the life, McCulloch exceeds the discourse of comparison between the living and the technical, exceeding the analogy[103], reaching instead for a way of understanding biological objects as originating from molecules that are *biological* computers. This is the origin story of cybernetics, consisting of a biological object that bears forward digital information in time on the basis of the form it takes. McCulloch's 'biological computers', as reproductive protein

---

[102] Though "Biological Computers" was eventually published in a journal associated with the Institute of Electrical and Electronics Engineers in 1957, this published paper is a very different from the document held at the American Philosophical Society Library. All citations refer to the archival document, and not the published document, W. S. McCulloch, "Biological Computers," *IRE Transactions on Electronic Computers*, vol. EC-6, no. 3 (1957): 190-192

[103] McCulloch, "Biological Computers," McCulloch papers.

molecules, carry information in their form unlike deoxyribose nucleic acids, which carries information in their code, an alphabetic patterning of nitrogenous bases. In this chapter, to clarify how matter's form relates to matter's information-carrying capacity, I also review McCulloch's analysis of the self-organizing quality of water molecules.

To understand the history of analogizing biological objects and machines, I turn to Georges Canguilhem's critique of Cartesian mechanistic thinking and the animal-machine theory in the lecture, "Machine and Organism," delivered in 1947.[104] Canguilhem reverses the anticipated direction of the comparison between man and machine, noting that there is a need for an *organology*, a study of biological organization without recourse to the descriptions of how machines, technical devices, function. Outlining the premise for an *organology*, he writes:

> Nearly always, the organism has been explained on the basis of a preconceived idea of the structure and functioning of the machine; but only rarely have the structure and function of the organism been used to make the construction of the machine itself more understandable. (45)

This is an argument to comprehend the biological principles underlying the construction of machines and to establish biological organization as primary.[105] Canguilhem establishes that "biological organization is the basis and the necessary condition for the existence and purpose of a machine" due to how machines (1) cannot construct themselves and (2) exhibit more purposiveness in than the biological organs to which they are indebted for the imagining of their form and operation. The biological organ is considered less purposive in that it is not trammeled to a single function, and in fact, possesses myriad purposes, undisclosed until their presentation in a manner unanticipated. The example given is of pediatric hemiplagia, a condition which, while having its origin in deadening brain tissue, does not often result in the loss of speech, "because the other areas of the brain ensure the continuance of the linguistic functions."[106] The other areas assume a purpose, a function, previously attributed to the tissue in the original, diseased area.

Though McCulloch's molecules, "biological computers," were derived from an assessment of the capacity of microscopic, reactive species to transmit information in the manner of a computer, in a preservation of the expected direction of organism-machine, what McCulloch does accomplish in the reverse direction is a questioning of information's context, information's materiality, the trappings of the world that constitutes it. Information, here, as always for McCulloch, is a physical phenomenon — in "Biological Computers," it is in the forms that matter takes, and in "Of Digital Computers Called Brains," it is the charge catching up in a

---

[104] Georges Canguilhem, "Machine and Organism," tr. Mark Cohen and Randall Cherry, in Jonathan Crary and Sanford Kwinter, eds., *Incorporations*. (New York: Zone Books, 1992), 44-69. On Descartes, Aristotle and the "body-as-machine" Canguilhem writes: "When dealing with the Cartesian theory of the animal-machine, it is often difficult to decide whether or not Descartes had any precursors for this idea…It is unquestionably Aristotle who saw the congruity between animal movements and automatic mechanical movements, like those observed in instruments of war, especially catapults" (48)

[105] "What I want to show is that the construction of machines can indeed by understood by virtue of certain truly biological principles, without having at the same time to examine how technology relates to science" Ibid., 45.

[106] Ibid., 59, 57.

membrane. However, in "Biological Computers," information is not merely reminiscent of a world, where the sending and receiving of electrical signals *reminds* one of physical laws at work in the world, but information is carried by the world - in the gentility of its form and in its watering of the brain. The animal experiments analyzed in Chapter 2 provided variables for how living systems successfully establish norms of nervous activity or fail to do so.[107] These variables were: blood sugar levels, levels of acetylcholine and cholinesterase. In this chapter, I will also analyze McCulloch's response to the life-question without such experimental metrics.

When considering how one could detect life on Mars, McCulloch submits a thought experiment in which a *simulation of man* would best detect life on Mars. Not man, but a simulation; not something living, but an approximation. Instead of a pharmacological brain capable of meting out responses on the basis of chemical inputs from a world as in the previous chapter, we now have an automaton capable of detecting life on planets besides earth. We have simulation of life detecting life, in a consummate amalgam of the vital and technical that has, we will suggest, a suggestive series of afterlives in the intensive care units of American hospitals[108]. To have a simulation of life responsible for detecting life is not as far fetched as it might seem if, as we have seen, life takes place in a chemical and electrical assessment of the world and in a chemical and electrical response to that world. The automaton functions as a kind of complex ruler, which, on Mars, *can* measure and perhaps re-enliven biological objects. McCulloch's medical and biological cybernetics, with its emphasis on pharmacological therapy and electricity, provides the basic principles for the engineering of machines now used in critical care: machines like mechanical ventilators and implantable cardiac defibrillators[109] – machines that run so close to life they are able to quicken even the living.

I. Water molecules, molecular biological computers, and a simulation of man as cybernetic responses to the life question

In "Biological Sciences", McCulloch and co-author Warren Brodey[110], study the relation of oxygen, Martian landscapes, and water to the question of life, but in "Automata model of man - MESM unveiled" McCulloch ultimately proposes a definition of life positioned on a *molecular* rather than ecological scale.

---

[107] See Canguilhem's discussion of the laboratory and the adjustment to environment: "If we may define the normal state of a living being in terms of a normal relationship of adjustment to environments, we must not forget that the laboratory itself constitutes a new environment in which life certainly establishes norms whose extrapolation does not work without risk when removed from then conditions to which these norms relate." Canguilhem, *The Normal and the Pathological,* 148-9.

[108] See Sharon Kaufman's discussion of implantable cardiac defibrillators, kidney dialysis and liver transplantation in her *Ordinary Medicine: Extraordinary Treatments, Longer Lives, and Where to Draw the Line* (Durham, NC: Duke University Press, 2015) as examples of "life prolonging interventions" that "reveal how the changing means and ends of technologies impact the goals of medical practice and patient sensibilities." (133)

[109] Ibid.

[110] On the psychiatrist Warren Brodey see Evgeny Morozov, "'A Bath of Continuous Sensations': Warren Brodey's Quest for Human Augmentation and Intelligent Environments, 1955-1975." Doctoral dissertation, Harvard University, Graduate School of Arts & Sciences, 2018.

> One class of … autocatalytic reactions is life. Its reproductive molecules are extremely large and correspondingly complex, but its bonds are not strong enough to ensure a long mean half-life, and its fields are too weak to compel perfect reproduction on all occasions.[111]

Here, imagining "reproductive molecules," McCulloch is coming to terms with the recent discovery of DNA, even if the term itself is not present in the text. Note the presence of physics in his considerations of how the molecules might reproduce themselves: "its fields are too weak to compel perfect reproduction on all occasions."[112] Even at the level of the molecule, the laws of physics are used as a conceptual resource, and in the quote above, the laws of physics are used in a conjecture on why life ends. It is a matter of insecure bonds and weak fields. McCulloch's reliance on natural law - in the form of the laws of physics - gives his evolving microscopic theories of physiological activity consistency as the grounds for a theory of world-building that is present in his response to the life-question. On a microscopic scale, world-building plays out apart from intention, in the utter evolutionary significance of the shape that matter takes. The world-building is present in the determinative power of the molecule's shape, and the information-carrying capacity of the form that matter takes.

McCulloch's texts in the later, post-DNA half of his career discuss life on a molecular level in relation to enzymes[113], the molecules composing water[114] and finally, in 1966, DNA, referred to in McCulloch's co-authored paper on the biological sciences.[115] In earlier chapters, I have argued that McCulloch's experiments on the structure of the nervous system and his electrical model of the brain require a consideration of a biological, medical cybernetics, in which the nervous system facilitates life-processes because the nervous system responds to a world that it has built and that it is in the process of building. Memory and the reflex response, which are not so distinct from each other in that they both are delayed responses to a world that has set them in motion, are both cybernetic phenomenon, inasmuch as they could be taken as physiological examples of the transmission of signals within feedback loops.

It is in "Biological Sciences" that McCulloch and Brodey discuss what affordances must be built into machines so that they might detect life on Mars, in what seems to be a commentary (and even meta-commentary) on his McCulloch's work. What would the machine need to detect life? What would I need to detect life? Ultimately, biological life becomes a process of metering the world's forces, a process best recognized not by a living being at all, but by a simulation of man in the form of a machine searching for life on Mars. Besides reporting on the state of the

---

[111] McCulloch, "Biological Computers."

[112] Ibid.

[113] In "Biological Computers," life is understood as a bio-molecular reaction driven by proteins called enzymes.

[114] In McCulloch's essay on the "Biological Sciences," written with Warren Brodey, there is a discussion of the "liveliness of water and its icy forms in biological organization." Warren McCulloch and Warren Brodey. "The Biological Sciences," in Robert Hutchins and Mortimer Adler *The Great Ideas Today, 1966.* (Chicago: Encyclopedia Brittanica Inc, 1966), 298.

[115] "A gene is an informed and informing process through which energy and matter flow as long as the system is alive. A gene is an encoded message, not the particular macromolecule or deoxyribonucleic acid on which it is located at a particular moment." McCulloch and Brodey. "The Biological Sciences," 303.

field of Biology, McCulloch and Brodey consider life on a terrestrial, extra-terrestrial and molecular scale, as perplexed by life's edges as he is by life's beginning. I argue that McCulloch and Brodey's reflections on the human body, the environment and the cell required a concept of the nervous system as a physiological system engaged in physical measurement of forces, in human and inhuman environments. McCulloch and Brodey's discussion of the information carrying capacity and self-organization of water molecules opened up the possibility for a theory of molecular information systems that differed from coding of the genetic program but that could not compete with the discourse of gene action[116]. I am not merely marking a loss, I am marking a method in the philosophy of biology, the cybernetic approach to the life-question.

II. Biology as biophysics

"The Biological Sciences," begins with a history of biology. The purpose of the series in which it appeared, *The Great Ideas Today*, was to circulate work across different fields, demonstrating the most significant developments to date.[117] In their paper, McCulloch and Brodey trace the ideas that they perceive as fundamental in contemporary biology from their ancient origins. The Greeks are cited for the following ideas, said to have afterlives in mid-20th century biology: first, the nerve-centered theory of knowledge; second, "equality of unequals,"[118] a political and biological idea where, in the same way that different persons are "all alike before the law" within the city-state, different components of health are all alike in their equal importance to the flourishing of the organism, disparate parts being required to harmoniously play together as a team; third, "general because best", where "the idea or form among many which is to be widely accepted has to be the one most likely to succeed"; and fourth, the teleology of living things, "hence our notion of function as the end in and of an operation." These ideas are loosely attributed to Aristotle[119]— the reason for presenting them is because McCulloch claims that *these ideas were the foundation of Greek medicine[120],* which in McCulloch's argument, then became

---

[116] See Evelyn Fox Keller, *Refiguring Life: Metaphors of Twentieth Century Biology* (New York: Columbia University Press, 1996) for a discussion of the force of metaphor in directing scientific research and how the discourse of gene action caused other discourses to obsolesce; for example, "the significance of the cytoplasm" (24).

[117] McCulloch's essay in the 1966 volume is followed by a translation and commentary on Ovid's *Metamorphoses* and is preceded by an essay on "Astronomy and the Physical Sciences," written by Hermann Bondi. Susan Sontag's essay "Literature" appears in the same volume.

[118] "…not only the foundation of their city-states but also of their biology: one, called the 'equality of unequals,' that no matter how dissimilar we may be we are all alike before the law, for health requires the harmonious team play of the man dissimilar parts severally necessary in living systems." McCulloch and Brodey, "The Biological Sciences," 290.

[119] "Aristotle, like Darwin, made rich observations, and biology received not only classification of genus and species but also the principles that underlie "bound cause" - that like begets like-the heart-centered and then the nerve centered theory of knowledge, and the foreshadowing of two other laws which were not only the foundation of their city-states but also of their biology…" Ibid.

[120] "These were the foundations of their great school of medicine" Ibid.

the foundations for Leonardo da Vinci's ability to theorize the knee joint as a lever[121], Descartes' ability to describe nerves as feedback devices, in the manner of "a thread returning up the nerve to shut its valve when its impulse had done its work on muscles" (290) , and Leibniz's ability to allow for cognitive activity (thinking, perceiving, feeling) as forms in motion: "…if he succeeds in making his computer so that it can think and perceive as feel as we do (and)…if we were to wander around within it, we would not see thinking, perceiving and feeling only forms in motion." (290) The paper is most significant for its rendering of philosophy of biology in such a way that it makes sense for cybernetics to exist; that is, the science of cybernetics is presented as the logical outcome of the intellectual history of nervous activity, automation, and form. References to Galileo, Descartes, and Leibniz immediately precede McCulloch and Brodey's discussion of the advent of neurophysiology beginning with the ability to detect the electrical activity of the brain.[122] Following a discussion of the contributions of Mendel and Peirce to information theory, McCulloch and Brodey introduce the contributions of Weiner, Rosenblueth and Bigelow and cite the McCulloch-Pitts neuron as an advance in understanding how mechanisms handle information[123]. For McCulloch and Brodey, the history of biology is the history of biophysics — and information is no exception. It is compared to thermodynamics as having the same end: "Information theory, like thermodynamics, is primarily concerned with limits of the possible." (295) For McCulloch, the idea that biological objects register and responds to the world's forces is the idea capable of explaining how cybernetics, as an expansive theoretical outcrop that jutted out from the Second World War[124] is in continuity with earlier movements in the philosophy of biology.

McCulloch and Brodey frame the paper by first delimiting what man is: an active physical structure that handles information for the purpose of learning. For McCulloch and Brodey, it is not enough to see man "as an active physical structure"[125], as matter that is dynamic in some patterned way. Instead, man must be understood as a *system* that is an 'active physical structure' "*handling information* in order to survive and in order to enjoy the most intimate forms of communication, which Donald McKay correctly calls 'dialogue.'" The McKay reference establishes the exchange of information within communication as a necessary condition for learning : "this (dialogue) enables man to learn as is necessary for the survival of the species." The argument about what man is reaches its culmination in a statement positing man's biology (its physicality, its systematization, and its capacity for learning) as a kind of physics: "Thus, our biology (like its counterpart in engineering) distinguishes work from energy and signal from

---

[121] "Modern biology begins with modern physics. Leonardo da Vinci, picking up where Archimedes left off, generalized the theory of the lever and understood properly the action of muscle and tendon at a joint-thus, functional anatomy." Ibid.

[122] "We had begun to understand some of the chemistry of the brain and were able to detect grossly its electrical activity, using capillary electrom- eters and galvanometers. About 1930 came modern amplifiers and then microelectrodes letting us look at the activity of single units. Modern neurophysiology got under way. Today one can scarcely keep up with its flood of publications." Ibid.

[123] The paragraph opens with "In 1943 new notions of mechanisms handling information entered the biological field." Ibid., 296.

[124] "[M]odern biochemistry of brains began and has shot ahead, in part out of our necessity to understand the nerve gases of WWII." Ibid., 290.

[125] Ibid., 289.

noise."[126] I argue that the ability of biology to distinguish between categories driven by forces in common with the rest of the world is biology's definitive quality in McCulloch's later work. Living systems make these distinctions, those between signal and noise, between work and energy, and I argue that such distinctions are able to be known and recognized by living systems because living systems build and respond to a world also organized by these distinctions. is that, in this paper, the notion of world includes what is beyond the earth.

Reflecting on scientific developments of the 20th century and describing the degree to which nuclear warfare and the science of radioactivity made it necessary to synchronously consider physics and life, McCulloch acknowledges changing conceptions of the atom. He writes on how the study of biology felt the "impact of the coming atomic age":

> In 1908, the atom ceased to be the simple, solid thing it had been…The pressing problems raised by our accelerators and by the threat of nuclear war have attracted many first rate young physicists, given them the tools and created the posts for a rapid development of radiobiology which is now receiving a new boost from the space age.[127]

One example of a post-war radiobiological problem is the risk that sunspots[128] pose to astronauts. McCulloch offers: "sun flares greatly increase the radiation in space by particles moving so fast that their weight is much augmented by their velocity relative to to the self-contained space capsule in which we must shield the astronaut and his biological environment" (291). Here, the biological environment is enclosed by a membraneous space capsule, and what makes the environment biological at all is the presence of oxygen; as he writes, "the space age has forced us to look into closed environments where chlorophyll is of importance in utilizing carbon dioxide" (291). This observation prompts a consideration of chlorophyll pigments, because chlorophyll is the compound in plants responsible for the light-capturing reaction that drives photosynthesis which ends in the production of oxygen gas.[129]

McCulloch's and Brodey's reflections on the health of the astronauts, the remarks on chlorophyll, and his emphasis the importance of oxygen, are also reflections on the world and conditions of life. The greenery in McCulloch and Brodey's account is surprising and singular, even if it is obvious that oxygen is necessary for the continuation of human life in space, what surprises is the degree to which this discussion of dirt, grass and space is one of McCulloch's

---

[126] Ibid.

[127] Ibid., 291.

[128] "This comes first from the hazard of sunspots; sun flares greatly increase the radiation in space by particles moving so fast that their weight is much augmented bu their velocity relative to the self-contained space capsule in which we much shield the astronaut and his biological environment." Ibid., 291.

[129] Note that photosynthesis is the reaction of cellular metabolism in reverse.

6 CO2 (gas) + 6 H2O (liquid) -> C6H12O6 (solid) + 6 O2 (gas)

Cellular respiration:

C6H12O6 (solid) + 6 O2 (gas) -> 6 CO2 (gas) + 6 H2O (liquid) + energy

C6H12O6 is glucose, the carbohydrate molecule that is produced during the photosynthesis reaction and is reduced (mined for energy) during the cellular respiration reaction occurring in cellular mitochondria.

response to the life-problem. In the same paper, McCulloch and Brodey address the question of whether there could be extraterrestrial life on Mars by considering (1) the production of oxygen gas (2) a water-based definition of living organisms and (3) the technology necessary for detecting extraterrestrial life.

In a typewritten lecture from 1945 on "Aviation in Medicine" McCulloch discusses the effect of flying on airplane pilots' central nervous system. McCulloch emphasizes the role of oxygen in cellular respiration, explicitly linking cellular respiration – referred to as metabolism[130] – to the propagation of electrical signals within the nervous system:[131]

> Today it can be said that the brain subserves its many functions of communication (prediction, homeostases and control) by a single type of mechanism, namely by the propagation of electrical signals throughout the length of its excited nerve cells…each such transient electrical impulse releases electrical energy stored in the vicinity of the cell-membrane as evidenced by a difference in voltage between the outside and inside of the cell. So far as the nerve-cell is concerned in the propagation of the impulse, it would not matter how this voltage had been secured, but in the living nervous system its only source is the metabolism of the nerve-cell and the generation of this voltage is known to be dependent upon the oxidative metabolism of carbohydrate.[132]

The lecture discusses the effect of flight on the nervous system of the airplane pilot. McCulloch describes how the regions of the brain which evolved most recently in human beings require the most oxygen and gives the example of the cerebral cortex for a tissue most at risk for failure when oxygen or glucose levels dip below a certain threshold[133]. The subject of the lecture is what defects can be expected in pilots during flight due to disorders of nervous function with decreasing metabolism[134]. McCulloch predicts a loss of activity in the cerebral cortex first, the loss of a pilot's critical faculties, the ability to navigate a strange port[135] on the basis of the meaning of lights, radiobeams and charted distributions[136] alone: "The first sign to be affected is a loss of critique. At low altitudes, interruption of oxygen supply over a short time, a matter of seconds, not merely results in a loss of critique but in a loss of consciousness and consequent failure to rectify the situation."[137] Supporting this statement is a description of the

---

130 McCulloch, "Aviation in Medicine."

131 Ibid.

132 Ibid.

133 "Not all parts of the brain have the same Oxygen requirement. In general, the more complex and highly evolved parts, such as the cerebral cortex, have a higher rate of corruption of oxygen than the spinal cord." Ibid.

134 "This is not the time to go into the deals of the disorders of decreasing metabolism." Ibid.

135 "The traffic laws of airports, the signal systems on the ground by lights and by radio for the pilot fo an airplane has not the symbol of an automobile but one much more comparable to the pilot who brings a ship into a port, often a strange port of which he only knows by charts the distribution and meaning of lights, radio-beams and what not." Ibid.

136 Ibid.

137 Ibid.

Electroencephalogram reading when a functioning respiratory system is provided with a mixture of Nitrogen gas composed of less than 5% Oxygen - the brain waves disappear.[138]

McCulloch remarks on the importance of o*xygen* for both astronauts and airplane pilots in a curiously elemental rendering of the conditions for life. There is also commentary on oxygen's maintenance of the metabolic reduction of sugars and the capacity of green chlorophyll to turn carbon dioxide into oxygen. In a dissertation on the nervous system's capacity to be in relation to a physical world that it builds, McCulloch's emphasis on the elements present in the environment that are necessary for nervous activity seems like it could destabilize notions of the nervous system's agency and world-building capacity; however, more readily they reveal a panic over a departure from a known world, and perhaps even the loss of a known world in a nuclear catastrophe. The work of the nervous system is to manage past and present responses to a world that the nervous system is also capable of changing, requiring an ability to hold different iterations of world in mind — the notion of a departure from the earth includes a loss of them all. Earth-bound objects can also serve as memory[139], so to lose the earth is also to lose the opportunity for the activity of perception our bodies are most prepared for. It is the loss of an environment that facilitates the first instance of nervous activity, considered as response to an insistent world. The future proves un-navigable in such an instance, because the matter that informs us to act in a future moment is lost. Without a world to which we are adapted, we lose the collection of projected actions and stimuli, that attune is to the fact of the past, the fact of a future. The risk inherent in the loss of the world's matter is the loss of the nervous system's time-keeping.

Concern for astronauts – "there comes first the hazard of sun spots"[140] – leads to a discussion of chlorophyll and the composition of the atmosphere at the origin of life: "what is more, the questions of extraterrestrial life, besides the problem of sterilizing everything to land, say on Mars, have compelled us to look at the varieties of chlorophylls, some of which require oxygen, others not, to account for our own atmosphere whose oxygen was probably all liberated in an originally reducing atmosphere of methane, ammonia, and perhaps, some carbon dioxide." McCulloch concludes that it is possible that there is life on Mars based on the composition of its atmosphere: "some Oxygen and much CO2" and based on an emergent working definition of life: "living things as we know them are chiefly water organized by macromolecules."[141]

III. The arrangement of water molecules as a model of self-organization

---

[138] "This can be seen in the disappearance of brain waves from the Electroencephalogram in insulin-coma or oxygen deficiency , produced by breathing mixtures of 5 percent or less oxygen in nitrogen , at a time when the respiratory mechanism continues to function normally." Ibid.

[139] Here, I am not merely extrapolating from McCulloch and Brodey's discussion of water molecules in "Biological Computers." I am thinking about what objects could be in opposition to Bernard Steigler's concept of the "technical object." Steigler writes: "The dynamic of organized inorganic matter, bearing tools, calls into play a force that is no longer of zoological (animal or human) origin, nor ecological (water and wind), but *industrial*, *that is, available independently of all territorial considerations*." Bernard Steigler, *Technics and Time*, vol 1: *The Fault of Epimetheus*, tr. Richard Beardsworth and George Collins (Stanford: Stanford University Press, 1998), 70.

[140] McCulloch and Brodey. "The Biological Sciences," 291

[141] Ibid., 291-2.

In “Biological Sciences,” McCulloch and Brodey approach the organizational capacity of the biological object, the brain, by looking to water as the key component of the semisolid material with which the brain is constituted[142]. The activity of water molecules as determined by the spin of electrons and valence electrons[143] serves as a physical basis for understanding not only the relationship between form and function in organic tissues[144] but also the relationship between form and information. The principal example is of the geometric structure of the water cage: vibrating shells of water molecules that “flicker” as they are constructed and deconstructed around other molecules and ions. Here, water is the object of study capable of demonstrating the a mode of interrelation, a dialogue, that emerges between different scales of organization. The problem that increasingly characterized the field of cybernetics was that of the relation between scales of independent, complex systems - so for example, the interactions between feedback loops[145] and not merely the content of any given feedback loop’s activity. When one circuit starts being in relation to one another, when two or more components are coupled, in between them, a dialogue or language exists, governing, not necessarily the independent activity of each, but how the activities of one are enfolded into the activities of the other. The physical laws governing this interrelation between scales is what is emerges as the object of study in McCulloch’s biological, medical cybernetics - “at every level and between levels there is a dialogue.” And this interrelation, this dialogue, is what is understood as information, the communication of which is sustained by the laws governing the physical world:

> Real brains are made of semisolid-state components whose physics we will next consider, because they are the biological substrate of man, real man able to enjoy dialogue. To him we will return from another angle. At every level and between levels there is a dialogue, we will start from the dialogue of H2O’s.[146]

To understand the conceptual importance of notions of scale to notions of life requires an adjustment to McCulloch’s assumption that physical laws are capable of explaining physiological activity.

---

[142] “Real brains are made of semisolid-state components whose physics we will next consider, because they are the biological substrate of man, real man able to enjoy dialogue. To him we will return from another angle. At every level and between levels there is a dialogue, we will start from the dialogue of H2O’s.” Ibid., 297.

[143] Ibid., 298.

[144] "To understand their formation we must note that in the bulk of liquid water the molecules and cages are tumbling about, and, therefore, the electromagnetic fields due to their valence electrons are on the average equal in all directions." Ibid., 301.

[145] “Even if each feedback loop is stable, the combination of several operating upon a given effector may produce destructive oscillations or lock the system in extreme position…there can be no general theory of non-linear oscillations.” Ibid., 297

[146] Ibid.

To introduce why the case of water molecules proves significant to thinking about the central nervous system[147], McCulloch and Brodey offer what follows, outlining a conceptual method of moving up from an atomic scale so to understand, ultimately, “man as a social being”:

> What one would like to do is to start from the ultimate particles, ready to model atoms so as to explain their chemical properties in forming molecules, and then deduce from this a proper model of their aggregations to explain the structure of micelles and organelles, and then from these deduce the structure of cells, thence the structure of tissues determining organs and organ systems and finally to present the organization of these system into a lively anatomy of social man.[148]

This “lively anatomy” would serve the purpose of a comprehensive model, a model capable of explaining man’s behavior based on man’s particles. McCulloch and Brodey acknowledge the limitations in doing so but at the same time claim that the current state of scientific thinking about the body is one that is more advanced than mere deduction[149] - given that theories of atomic structures (electron spins and valence electrons) are used to “(1) imagine the behavior atoms (2) to design instrumentation and (3) to interpret their results in order to determine the momentary organization.”[150] Water, understood as molecules of Hydrogen and Oxygen, is the case chosen to demonstrate how the physical qualities of the components of biological material[151] determine the patterned activity of larger scales of organization. McCulloch and Brodey describe (1) Shedlovsky’s experiment in which water’s ability to conduct electricity was what allowed the consideration of membranes as capable of carrying voltage and transmitting charge. Shedlovsky’s experiment made progress on developing a “clear theory of thermodynamics for open systems” because, based on water’s “proton hops” (298), current could be carried and transmitted by a membrane like the neuronal membrane that carries and transmits the action potential. McCulloch and Brodey discuss the electrical consequences of water’s activity in their understanding of the Shedlovsky experiments:

> Then Shedlovsky showed that over 80 percent of the conduction of electricity by pure water was due to proton hops and not to the migration of OH- or H2OH+ ions. He constructed a membrane of thin, soft glass, permeable to H+, covered by a thin layer of an insoluble barium soap of a simple 10 Carbon acid. With the same solution on both sides of the membrane, it produced voltages comparable to those of cell membranes. Just as a battery, by separating locations of oxidations and reductions can produce a current

[147] See their discussion of squid-axon experiments.

[148] Ibid., 298.

[149] “While we do use theories of atomic structures such as the spin of electrons, valence electrons, etc., to help us (1) to imagine the behavior of atoms, (2) to design instrumentation, and (3) to interpret the results in order to determine their momentary organization, the process is far from a pure deduction.” Ibid., 298

[150] Ibid.

[151] “Whatever else a neuron is, mathematically it is a highly nonlinear oscillator. Note that we have been speaking of purely logical and mathematical problems which, regardless of the physics of the system considered, might be made of hardware of any description.” Ibid.

> over a metal that conducts only electrons, so by separating acid and base by a membrane that conducts only protons, a current can be obtained.[152]

This was a pre-war experiment. McCulloch then notes how, during the war, developments occurred "forcing biologists to look more into the structure of water in living systems"[153]: (1) studies of explosive decompression of tissues which allowed for studies for how particles can serve as a seed for "bubble" formation (2) microelectrodes and the ability to insert instruments sensing electrical activity into the neurons of squids (3) Szenty-Gyorgi's experiments on dye in ice and in water, discovering that the dye fluoresces in water but not in ice. What McCulloch postulates by outlining these three war-time examples is that the chemical composition of water in tissue was not enough to determine or to understand what happened when that tissue (1) underwent physical changes (2) possessed a voltage that was measured and compared to known voltage values for a given chemical compound (and differing from the known values even though chemical composition should have predicted the standard electromotive force for that mix of compounds) and (3) was discovered to cause dye to phosphoresce instead of fluoresce[154]. He offers, "Here, again the living system cannot be explained by the chemistry of solutions"[155] meaning that the structure of the water (299) and not the chemical compounds in circulation possess the potential to explain why certain muscle tissues have the properties they do. The argument is that it is not chemistry that is capable of explaining the incongruities of the body's physiology: it is the structure of the molecule, which derives from how the laws of physics act upon and are iterated within that structure.

McCulloch and Brodey then describe how physicists have been studying water: "the structure of water was first discussed in the modern crystallographic sense by Bernal and Fowler in 1933. The authors were concerned with X-ray scattering, dielectric constants, and with the extra mobility of the hydrogen ion in acid solution from a quantum - mechanical point of view." McCulloch and Brodey locate the implications of this work in the bonds that water molecules form *with each other*. They talk about the crystal structure of ice as well as his own work with Berendsen on the geometric structures of "water clusters":

> Throughout this range, there must still be bonded clusters of many molecules even if some are separate. At 10^-12 seconds, the molecules can only vibrate. Frank and Wen in 1957 aptly described these clusters as flickering, in the sense that they are always rapidly forming and breaking up.

---

[152] Ibid.

[153] Ibid.

[154] "Fluorescence occurs much more quickly than phosphorescence. When the source of excitation is removed, the glow almost immediately ceases (fraction of a second). The direction of the electron spin does not change. Phosphorescence lasts much longer than fluorescence (minutes to several hours). The direction of the electron spin may change when the electron moves to a lower energy state."
Helmenstine, Anne Marie. "Fluorescence Versus Phosphorescence." ThoughtCo. June 02 2019. Accessed Nov. 18 2020. <https://www.thoughtco.com/fluorescence-versus-phosphorescence-4063769phosphorescence-4063769>

[155] McCulloch and Brodey. "The Biological Sciences," 299.

What McCulloch achieves with the example is a physical rendering of information exchange outside of DNA - “this speaks to some form of cooperative process” (300). The Berendsen and McCulloch model that McCulloch self-referentially presents is of an ever-changing, “flickering” model of liquid water, capable of “entering into various structures in many ways.”[156]

At certain moments in the formation of water molecules with each other, there are bifurcations. There are discrete “transitions”:

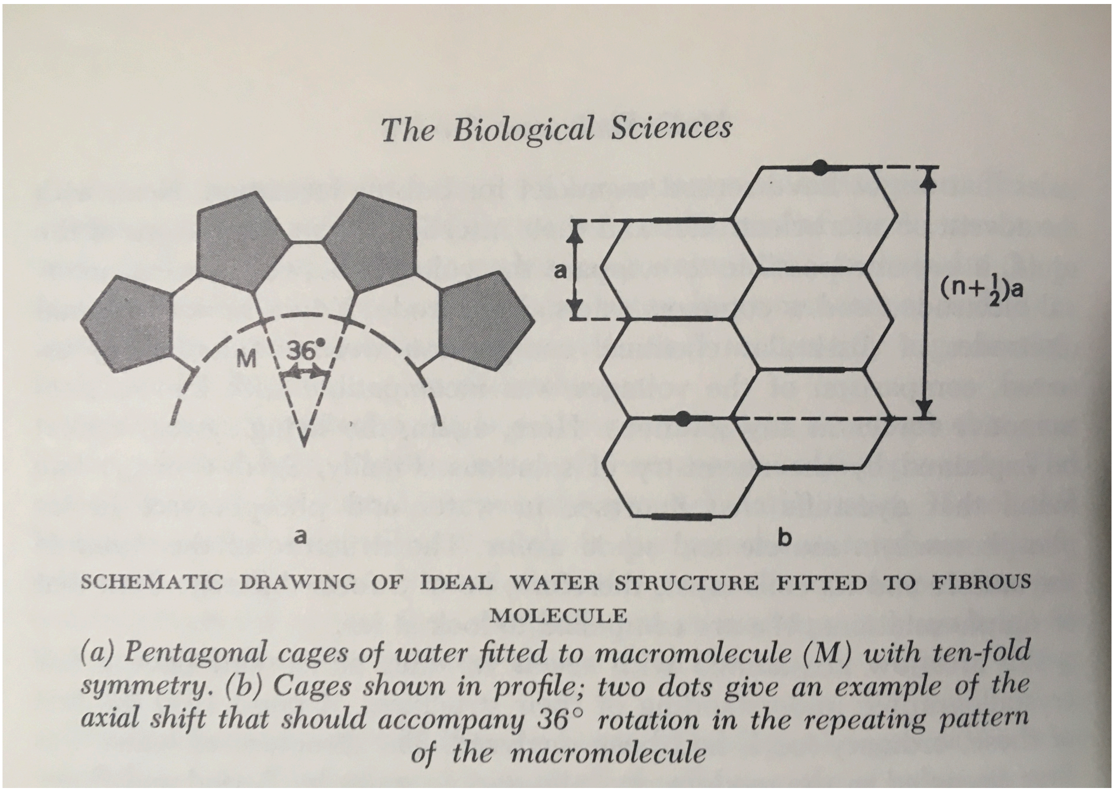
> Almost every measurement that has been made with sufficient precision over a large range of parameters, whether of pure water, solutions, or emulsions, if it could possibly depend upon the aggregation of water into structures showing sharp transitions. This bespeaks some form of cooperative process. If the formation of a hydrogen bond between two water molecules promotes the hydrogen bonding to the complex, and it takes the breaking of many bonds to destroy the whole structure, we have a proper model.

McCulloch and Brodey are referring to what is called a pentagonal model of the water molecule in a departure from the linear model of water molecules devised by Ising, in which the departure of one water molecule from a long chain due to a disturbance means breaking a link in a long chain - where the break in the chain would expand as the temperature gets higher. McCulloch and Brodey claim: “This is exactly what does not happen.” In McCulloch and Berendsen’s model of the interrelations between liquid water, there is an accounting for short-range forces between molecules “instead of long range forces” and for the neighboring relations instead of the isolated molecule and for three dimensional geometry instead of a line.[157]

---

[156] Ibid.

[157] Ibid., 300.



SCHEMATIC DRAWING OF IDEAL WATER STRUCTURE FITTED TO FIBROUS MOLECULE

(a) Pentagonal cages of water fitted to macromolecule (M) with ten-fold symmetry. (b) Cages shown in profile; two dots give an example of the axial shift that should accompany 36° rotation in the repeating pattern of the macromolecule

Figure 4: Structure of water molecule from "Biological Sciences"

The model specifies the form the molecules take, resembling 5-figured water cages or water shells known as "calthrates." (Figure 4). McCulloch describes the pentagonal model as a solution to the problem of water chain extension and decay. The pentagonal model is five water molecules hanging together:

> The simple problem has now been solved for the square array in which each component is held in place by its four neighbors (but not for three dimensions). These structures are stable up to a critical temperature, a 'melting point,' above which they break down rapidly.[158]

The pentagonal model serves as a physical model of information in which form is exchanged for code, "here [in the pentagonal model] a proper physical analogue of Shannon's famous coding ensuring information theoretic capacity." The rotating water molecules in the cluster, which hold until a specific temperature threshold because of their relation to one another, are able to communicate by way of this asymptotic system[159] - at a certain level, coherence, at another level incoherence - in their formal integrity they are the *material* corollary of a system that has the capacity for "information theoretic capacity." The water clusters, in their form and in their conformational changes, constitute the very material of information.[160] The significance is that, for McCulloch there could exist a material means of engaging in dialogue between scales of organization. Rather than saying that the brain's informational capacity is solely dependent on the formal changes of water molecules, McCulloch is saying that there exists in the body - outside of DNA - notions of code that are *formal* not alphabetical or programmatic, that are conformationally constituted on the basis of shape rather than identity-constituted on the presence or not of a given nucleotide base (G, A, T, C, U). This notion that form can carry code in and of itself is not solely a commentary on chemical architecture and its affordances, rather it is a commentary on how the environment becomes part of the brain's informational capacity, a commentary on the brain's ability to recognize and make use of the world's forms.

IV. The physicality associated with Information Theory

In "Biological Sciences," McCulloch and Brodey contrast the speed[161] at which biophysics has contributed to the discipline of Biology with the slow contributions of genetics and studies of heredity and evolution. The exceptions to this slowness of genetics and studies of heredity and evolution are Gregor Mendel's studies of hybridity and Watson and Crick's discovery of the

---

158 Ibid.

159 See René Thom, *Structural Stability and Morphogenesis; an Outline of a General Theory of Models* tr. D. H. Fowler (Reading, MA: W. A. Benjamin, 1973), for a discussion of the topological models of developmental, embryological change. His ideas rely on the notion of the asymptote as some value threshold, over which radical deviation from a prior process occurs.

160 McCulloch and Brodey, "Biological Sciences," 301.

161 "Contrasted with theses rapid and urgent contributions of biophysics and bioengineering, the natural pace of biology is slow for many reasons." Ibid., 292.

double helical structure of DNA (Roslyn Franklin is left out). Mendel's studies of hybridity using the cross-fertilization pea plants marks for McCulloch the nascence of theoretical biology[162], which is a mathematical biology, and which is most important for laying the groundwork for biophysics:

> Mendel, with a training in mathematics and physics as well as in horticulture, proceeded like Galileo and like Descartes, by postulating miniature entities invisible to him - we call them genes - and a hypothetical mechanism of their relation, to predict the observable traits of their offspring in ratios approached by adequate samples. (293-294)

Theoretical biology is identified by way of its method: predicting the behavior of indivisible units. McCulloch continues, establishing Mendel's method as an archetype: "This is a truly mathematical biology, employing algorisms [sic] to compute the expected number of phenotypes in successive generations"[163] and "Mendel's use of postulated unitary entities has been followed by the pioneer scientists in vitamins, hormones, and enzymes so that today there is a great body of truly theoretical biology leading us to an appropriate biophysics" (294). As to why McCulloch would spill ink over Mendel's experiments as the experiments that developed the conceptual framework for theoretical biology in its subject matter (the unit), scale (miniature), and purpose (predictive) — it is to set up an argument about the gene as not a physical object but as a physical process.

If the gene is an activity, then it can be modeled as a process bound by the laws of physics and projected into the future. Under such assumptions, the gene becomes predictable as a force and not as matter susceptible to force. McCulloch warns of the "danger" of considering the gene as a physical object: "There is always a danger to be avoided here — a particular chromosome, say the X chromosome of man, is not the physical object one sees under the microscope any more than the letter *x* is the ink you see on this piece of paper. *A gene is an informed and informing process through which energy and matter flow as long as the system is alive*"[164] Information and the origin of the theory of information are alluded to in this final statement - as well as in the metaphor that exchanges material existence for a formal one - not the ink that you see but the letter, not the physical object but the form according to the activity (reading) that it participates in.

C. S. Peirce serves as McCulloch and Brodey's interlocutor when considering the origins of the theory of information, invoked to discriminate between the material component of the symbol and the material component of the thing symbolized: "Peirce was at heart a pansomaticist like the Stoics, and his symbol, like the thing it symbolized, was a physical thing. So also was the brain of the man, speaker or listener, who used the symbol" (295). Though it may seem confused to consider a form, as the thing symbolized, *material*, McCulloch interpreted the thing symbolized, the information, as electricity in the wire, which in the electrical model of the brain,

---

162 "It marks the beginning of today's theoretical biology." Ibid., 293.

163 Ibid., 294.

164 Ibid. My emphasis.

constituted the circuit action[165] of thinking. Electricity is a physical phenomenon and is formal to the extent that it causes other matter to take shape. McCulloch and Brodey cite the origin of the theory of information in a single experiment - in 1927 at Bell Telephone Laboratories, where a machine quantified the amount of information in the speech of a human being[166]. And so information theory is defined as the theory "concerned with how much redundancy is needed to ensure a message transmission with given probability of success when there is noise, specified in amount and kind, on the channel." McCulloch and Brodey cite Claude Shannon to discuss two principles of information theory that are biologically important, summarized here:[167]

> (1) In a complex system with an optimum code (e.g. the code of nucleotide bases, Adenine, Tyrosine, Guanine, Cytosine, so A, T, G, C) a code chosen at random (e.g. CATG) will be equally as optimal as any other code (e.g. TCAG)[168]
> (2) Even given noise, understood by its definition in physics[169], there exists a code[170] that can be accurately communicated with few errors so long as the *channel* the information is transmitted through has a capacity that is higher than the amount of information being transmitted.

Point (1) is a direct reference to the structure of DNA, with the inclusion of the discussion of the nucleotide bases in a discussion of information. McCulloch defines information as negative entropy[171] and he also compares information theory with thermodynamics, in a clarification of information theory's role in the history of science — "Information theory, like thermodynamics, is primarily concerned with limits of the possible. The former tells you nothing of how to make a code, and the latter tells nothing about particular affinities of reacting components."[172] The stringing together of information and thermodynamics, where information has been defined in

---

[165] "For our object is to set up working hypotheses as to the circuit action of the central nervous system as a guide to further investigation of the function of its parts, and as a scheme for understanding how we know, think and behave." Ibid., 369. Cf. McCulloch and Pfeiffer. "Of Digital Computers Called Brains," *The Scientific Monthly*, 69:6 (1949).

[166] "Similarly, when information theory began about 1927 at the Bell Telephone Laboratories, the problem was how much information is conveyed by human speech turned into electrical signals on a wire and understood by the human listener." Ibid., 295.

[167] "In Shannon's elegant development from the most realistic assumptions, two surprising theorems result, both of which are biologically important. The first is that for a sufficiently large ensemble of messages, while there is an optimum code, almost any sufficiently complicated one chosen at random is almost optimal; and the second, that there exists a code by which one can transmit over a noisy channel with almost no errors provided one does so at less than the capacity of the channel." Ibid.

[168] Ibid.

[169] "Taking into account the statistical nature of this theory, it is not surprising that information can be equated to log p which is a pure number,
and the same pure number as appears in K2p log p of entropy in thermodynamics where K has the dimension of energy. For this reason information is frequently called neg entropy, as if it were a physical thing." Ibid.

[170] Ibid.

[171] Ibid.

[172] Ibid.

terms of the physical categories guiding its expression (noise, channel), is not incidental: it is representative of a form of thinking comfortable with the merging of physics and life. Thermodynamics is the study of energy exchange, and one of the quickest definitions of life is that of the metabolic organism as matter capable of extracting, transforming and releasing energy culled from its environment; however, this is not merely a metabolic definition of the organism. Instead, we have an organism as a density, a concentration of matter at the whim of energy, where information partners with thermodynamics to maintain the coherence of the matter and form subtending life. The two theories, information and thermodynamics, are described as articulating "the limits of the possible,"[173] where information theory and thermodynamics proffer a future in which the mechanics they aspire to are irrelevant, leaving us with the possibility of code and not how to code, the possibility of energy exchange and not the components, which if run together in a reactive silt, will produce energy. This is also the possibility of thinking, feeling and perceiving and not physiologically how those cognitive activities are accomplished. With this conceptualization of physics and organization, where information only can emerge from and within *matter*, McCulloch, the neurophysiologist, offers not descriptions of the organism's behavior as in "A Logical Calculus of the Ideas Immanent in Nervous Activity" but an ontological status. This is a biological object that is not representational, but actual and at some thickening, the result of the work of information and thermodynamics.

McCulloch and Brodey turn from Peirce, in their history, to the wartime period and to how engineering made progress on biological questions, principally through the consideration of what concepts govern cognition as a physical phenomenon:

> In 1943, new notions of mechanisms handling information entered the biological field. Craik looked on the nervous system as a calculating machines able to model its world and so to be able to think about it and explain how it worked. Wiener, with the mathematics, Rosenbleuth with the physiology, and Bigelow, with the realization that for governance one only needed information of the outcome of previous acts, described the mechanism guiding purposive behavior.[174]

McCulloch describes how engineers, more readily than biologists themselves[175], were able to consider the role of information processing in biological systems. The interventions arrived in the form of "new notions of mechanisms handling information"[176]. McCulloch describes the interplay of his own ideas with Turing's and what assumptions were held in common:

> Pitts with the mathematics and McCulloch, with the biology, proved that circuits made of such simple threshold devices as formal neurons could compute any number that a Turing machine could compute with a finite scratch pad. (296)

---

173 "Information theory, like thermodynamics , is primarily concerned with the limits of the possible." Ibid.

174 Ibid., 296.

175 "In each case the engineers have been quicker to pick up these developments of theoretical biology than the biologists themselves." Ibid.

176 Ibid.

The scratch pad is a reference to the Turing machine, whose computations as code are performed on a slip of paper fed into a machine. McCulloch and Pitts's model of nervous activity in "A Logical Calculus of the Ideas Immanent in Nervous Activity" corroborates Turing's conclusions by offering a formal model for cognition that is universal, easily transposed upon neuroanatomy or hardware, in such a way that cognition as a process in one system is isomorphic with cognition in any system – an organism or a man-made device, even if the structures that support the activity differ:

> As Turing clearly stated, a properly constructed computing machine obviously can think and perceive and care even as we do. We conceive ourselves to be such machines. Our difficulties lie elsewhere .… The problem of purposive, homeostatic, or controlled behavior which is the central theme of cybernetics is up against our inability to foresee what will happen when two or more components are coupled.

The assumptions articulated here – that computing machines can think and perceive and care, and that man is identified reflexively in the machines that he builds – are not merely those held by McCulloch and Turing. The "our" is more general, including the contributors to the field of cybernetics over its history. In place of the question of whether machines can think, there is the question of scale in biological systems: "the problem of purposive, homeostatic, or controlled behavior which is the central theme of cybernetics is up against our inability to foresee what will happen when two or more components are coupled."[177] In considering the neurophysiological structure associated with cognition and information processing, there is also a consideration of matter, and what extends beyond the act of cognition, what gives purpose to the outward-oriented structure of the sensorium. The environment is not an omission in McCulloch's calculus. Its laws are the content the cortex works over. McCulloch writes how, if the input from the environment is not identical to pre-recognized patterns in the basal ganglia, the inputs are transferred upwards, to the cortex, "the case is referred 'immediately' (i.e. within .1 second.)"[178] The cortex then "guesses at a law," guesses at what world could produce such a pattern, such a set of inputs.[179] The cortex devises habits on the basis of its guesses, suggesting a world and responding to the world it has suggested.

V. Simulations of man

Based on the claim that the Martian "white polar caps [were]… thought to be icy,"[180] McCulloch and Brodey conclude that there will soon be technological instruments that will be able to detect life on Mars because such instruments will have vision[181]; such instruments will be able to track

---

[177] Ibid.

[178] Ibid.

[179] Ibid.

[180] Ibid., 292

[181] Also, McCulloch takes up NASA's definition of life at the time: "a process of growth, reproduction and movement of some kind." Ibid., 292.

the movement that is one of NASA's criteria for a living thing: "But to detect movement they would like something comparable to vision. The communication back to earth is too poor and too slow to relay back televised pictures frequently for us to judge of motion. Our device must have ways of detecting it and noting shapes moving and at rest" (292). This ability to register (1) shape (2) motion requires an instrument that can think, and therefore, a computer[182] — and ideally, a simulation of man himself[183]. McCulloch and Brodey describe how man would be best suited to assess life on Mars but that sending man is impossible and so a simulation of man might replace man as a detector for life:

> There are many hostile environments, and sometimes simple requirements of size, weight, and speed preclude our sending a fellow man. To replace him with proper simulation in hardware, requires that we know well what he does, and because, he has evolved to do it well, it pays to know how he does it. Such simulations created bionics, which has joined the biologist, and the engineer in working teams to the advantage of both.

For McCulloch, thinking has never been an activity that is unique to human, biological life, but in this example, in the inherent distance between man and his simulation, there is a gesture towards a humanness that is not replicable – a humanness that even in its *limit condition* (not being able to travel safely to Mars due requirements of size, weight and speed and the harshness of the environment) marks man from his simulation but also leaves us with a curious instance in which man makes a machine (a simulation of a knowing organism) that is better able to assess life than he is, with faculties designed for the marking and processing of criteria man has independently set for life. Given McCulloch's training as a clinician, it is unsurprising that a technical ability to assess for extraterrestrial life would be considered in relation to the technical ability to assess for life in contemporary medical practice. McCulloch and Brodey establish a connection between the problem of life of Mars and the problem of diagnosis pathology in the clinic: "The problem of telemetering significant measures of life processes, or of hooking the living system directly to a computer, have produced team play, generally fostering a new field of bioengineering. Today there are machines teaching differential diagnosis and there are prospects of automated clinics as well as artificial pacemakers for failing hearts and artificial kidneys."[184] McCulloch transposes the telemetering capacity of artificial intelligence measuring life on Mars to the telemetering capacity of prospective medical interventions - interventions for failing hearts, failing kidneys. On Mars, McCulloch imagines a man "replaced with proper simulation in hardware" – a simulation of man capable of detecting life. On earth, devices for measuring life processes are also imagined as simulations of man. The ability to sense life processes requires the foreignness of Mars, the alien quality of Martian life, to imagine a simulation of man measuring life processes within fellow man. The extra-terrestrial landscape is a necessary conceit, intervening between the notions of man as simulation and the detection of life by that

---

182 "The device for detecting movement and shape must have some ability to think, therefore, some computer, to select and compress the significant data." Ibid.

183 "To replace him with proper simulation in hardware requires that we know well what he does, and, because he has evolved to do it well, it pays to know how he does it." Ibid.

184 Ibid., 292.

simulation, because, on Mars, life is not given in advance. Mars offers a conceptual outcrop for what it would be to set criteria for the determination of life, in quantity and in values, without the assurance that it was ever there. This is not the moment of death, where the assessment of life begins from an understanding of life's absence, but rather from a moment prior to or in front of an origin, and on the subject of what would be the criteria for life, then.

In the 1967 paper "Automata model of man - MESM unveiled" (Motor Innervated Simulating Model[185]), McCulloch similarly describes a simulation of man, here termed the humanoid model[186]. The paper is organized around the following questions that relate to different scales of organization that McCulloch perceives within man - the cellular (metabolic), the organs (nervous innervation of muscle, muscular activity) and behavior (sexual reproduction): (1) "How is it that the metabolic process is regulated to continue the movement?"[187] (2) "How is it that the movement is regulated to continue the metabolic processes?"[188] (3) "How is it that reproduction ensues?"[189] McCulloch writes about how the humanoid would need to behave according to the satisfaction of 'poles' of behavior:

> In man, there seems to be internal physiological endowment for 'knowing' its internal states, as well as external states. (In what sense 'knowing' is meant or carried on is irrelevant at the moment.) Archaeological-anthropological-sociological-biological study seems to suggest that there are definite 'poles' of behavior that must be satisfied and others that likely have to be satisfied. Thus boundary conditions can be specified (i.e., games can be played), in which we can be immersed and a pattern of behavior will emerge. Descriptively, perhaps stochastically, the patterns can be described, at least for limited periods (namely - seconds, minutes, hours, days, months can be discussed ....[190]

The ability to sustain a pattern among the poles[191] McCulloch considers the first task in building a successful humanoid model[192] as this behavior along a continuum between opposite states would account for the consequences of human physiology[193] as it would account for the system's ability to "eat, void, breathe, drink [and] become anxiously unstable to keep going over its polar check list"[194] — and more curiously "euphorically stable enough to persist in its orbits for

---

185 In a note at the end of the file for "Automata Model of Man - MESM unveiled," in what I believe to be McCulloch's handwriting, it says "MESM means Motor Innervated Simulating Model).

186 "However a successful functioning humanoid model could be built that will take care of the patterning among poles." McCulloch, "Automata Model of Man - MESM unveiled."

187 Ibid.

188 Ibid.

189 Ibid.

190 Ibid.

191 Ibid.

192 Ibid.

193 "For example, it certainly can satisfy physiology." Ibid.

194 Ibid.

awhile."[195] McCulloch acknowledges but defers "large philosophical questions"[196] in relation to the humanoid, suggesting that to begin to conceive of a humanoid model requires attention to the changes in state that result from inputs from the environment and not such questions as "what is large memory, what is consciousness, what is the meaning of life."[197] The mind-body problem is acknowledged and defined in an early portion of the paper as "the distinction between responses that may be 'wired' from input to output by direct mechanistic paths, or those that require a vitalistic, indeterministic volitional conscious system interposed. "[198] McCulloch further explains the distinction in relation to internal inputs and external inputs, where the distinction between 'mind' and 'body' fades and instead there are only internal inputs, as given a longer time frame, external inputs can be so slowed down, they can begin to seem to be the body's response to itself: its milieu. Inputs from the world, understood as *cues* from an external environment:

> Much of the metaphysics argument can be avoided if we recognize that our present concern is the result of more changes in the state of internal inputs - i.e., to the central nervous system - rather than to external inputs. In this longer time scale the external inputs now appear as quasi-static systems of much slower 'cues', that is, a slowly changing D.C. environment. (One day is much like another, and one week like another.) Thus it is essential to embed a given animal into a fixed milieu.[199]

The milieu coalesces when the scale of analysis is stretched, stretched so far as to see the inputs from the environment arriving not as stimuli but as slow, omnipresent reminders of place, that do not appear to be of external origin at all. McCulloch takes a critical tone in his reference to the volitional consciousness of vitalism and the metaphysics argument, but his is a kind of "vitalism without metaphysics," an impulse from the world that travels so slowly that its external origin is forgotten.

VI. Life is a biophysical phenomenon as an autocatalytic and self-reproducing reaction

In "Biological Computers" (1957-1958), McCulloch explores the differences between the biologist and the engineer, addressing the underlying question, w*hat is the difference between the biologist and the engineer*, or rather, *who is the biologist?* The first claim is that the biologist understands the physics of components in living systems: physics and chemistry are deemed equally necessary for both biology and engineering — biologists use physics and chemistry to "understand the physical components and their physical relations in living systems"[200] whereas

---

[195] Ibid.

[196] "We cannot start from the large philosophic questions: what is large memory, what is consciousness, what are values, what is the meaning of life, etc." Ibid.

[197] Ibid.

[198] Ibid.

[199] Ibid

[200] McCulloch, "Biological Computers."

physicists “understand the physical components and their physical relations in artifacts”[201]. The examples McCulloch provides of “artifacts” are steam engines and computing receivers[202].

The second claim is that the biologist proceeds without the awareness that attends being the creator of the object of study: “The chief difference (between the engineer and the biologist) arises from this — that the engineers’ machines are built to his own specifications. He knows what they are to do and how they are to do it. The biologist has to find out these things for himself”[203]. The third claim is that the biologist cognizes how the living system is capable of producing a useable output:

> Nevertheless the engineer has troubles. Despite his knowledge of the theories of entropy, of information, of games - and of multiple close-loop servo systems - he finds it hard to ensure a useable output from his most complex digital computers. Then he turns to his puzzled friend – the biologist – and asks “how does nature do it?”[204]

The final question is rephrased in subsequent sentences as not “how does nature do it?”[205] but “how does nature stabilize a useable output of complex computers?”[206] and McCulloch’s response to this question organizes his intervention: a definition of life understood as an autocatalytic[207] and self-reproducing reaction, catalyzed by molecules which, as molecular computers, produce the output of living systems. Biological-life-as-reaction is a precept in the piece “Biological Computers” for a theory of evolution, which acknowledges stability as the basis for heredity - a stability that is both logical and structural, digital and biological. The first argument is that useable output[208] is produced by particles that are able to induce forms of activity in other units of matter, what McCulloch describes as an ability to “induce in our world”[209]. The argument begins with a discussion of “ultimate disparate particles of atomic

---

[201] Ibid.

[202] “But physical sciences alone are inadequate for biology for exactly the sam reasons that they are for the engineer- engine, including computers, must work reasonably well if they are rapidly scraped. So must living systems.” Ibid.

[203] Ibid.

[204] Ibid.

[205] Ibid.

[206] Ibid.

[207] “Atoms again differ discreetly in kind. Their complex but weaker fields of force permit only certain configurations of atoms, some of which persist long enough to be identified as…molecules. The still weaker and still more complicated fields of force of some molecules suffice to promote the formation of more molecules of the same kind. One class of these autocatalytic reactions is life. Its reproductive molecules are extremely large and correspondingly complex, but its bonds are not strong enough to ensure a long mean half-life, and its fields are too weak to compel perfect reproduction on all occasions.” Ibid.

[208] “Despite his knowledge of the theories of entropy, of information, of games - and of multiple close-loop servo systems - he finds it hard to insure a useable output from his most complex digital computers.” Ibid.

[209] Ibid.

physics"[210], and McCulloch locates the basis for biological catalytic activity in the susceptibility of physics' "ultimate disparate particles"[211] to force:

> The ultimate disparate particles of physics are defined by their trajectories in electric, magnetic, ad inertial fields. Limited by the number of distinct least trajectories. Two particles, alike except that one is the mirror image of the other, on meeting annihilate each other. This reduces the number of kinds of particles that can induce in our world . The Strong forces that these compatible particles exert upon each other determine configurations, some of which are sufficiently stable for the chemist to call them atoms.[212]

McCulloch perceives the motion of elemental particles, "defined by their trajectories in electric, magnetic, and inertial fields" in the possibility that atoms of opposite charges can be self-annihilating, "two particles, alike except that one is a mirror image of each other on meeting, annihilate each other, and the strong forces that this self-annihilation exhibits requires certain physical forces that determine the particles' structure, forces which "the compatible particles exert upon each other" and which "determine (their) configurations."[213] McCulloch describes the spontaneous behavior of sub-atomic particles to access the possibility that the movement and activity of one disparate piece of matter could give rise to the *form* of another – the configurations, which result from the forces that compatible particles exert on each other.[214]

VII. The structure of an offspring molecule is what bears information forward in time

The second argument in "Biological Computers" is that, in the same way that the elemental particles of physics[215], are able to bring about a transmutation of form in the particles that they act upon, so can the reproductive molecules of biological systems, by their spontaneous activity, "promote the formation of more molecules of the same kind."[216]

> Atoms again differ discreetly in kind. Their complex but weaker fields of force permit only certain configurations of atoms, some of which persist long enough to be identified as…molecules. The still weaker and still more complicated fields of force of some molecules suffice to promote the formation of more molecules of the same kind. One

---

[210] Ibid.

[211] Ibid.

[212] Ibid. The ms. reads "Shong" instead of Strong.

[213] Ibid.

[214] Ibid.

[215] "The ultimate, disparate particles of physics are defined by their trajectories in electric, magnetic, and inertial fields." Ibid.

[216] Ibid.

> class of these autocatalytic reactions is life. Its reproductive molecules are extremely large and correspondingly complex, but its bonds are not strong enough to ensure a long mean half-life, and its fields are too weak to compel perfect reproduction on all occasions. A few times in a hundred thousand the product is discreetly different we call it a neutant. When in its environment it is a stronger catalyst than the original molecule, it replaces the original. Such is evolution.[217]

The relationship is not analogical, but physical – the same physical forces are shared by each, the atoms and the reproductive molecules. Unlike atomic configurations, which have (1) long mean half lives and (2) strong fields to induce the formation of more molecules of the same kind, reproductive molecules do *not* compel perfect reproduction on all occasions, as they have a short mean half live and weak fields which result in errors in the reproduction process: "A few times in a hundred thousand the product is discretely different we call it a neutant."[218] McCulloch pitches evolution in the terms of physics, where the neutant molecule might have a greater ability to induce the autocatalytic reaction that is life than the original molecule. When the neutant molecule is a "stronger catalyst" than the original molecule, the neutant molecule is regenerated instead of the original molecule — that is, the neutant molecule would be replicating itself instead of the original molecule replicating itself. This neutant and mutant molecule, replicating itself, replaces the original. This theory of evolution is one that is (1) molecular and (2) reliant upon the environment to apply selective pressure. When speaking to the the mutant's ability to be substituted for the original, McCulloch writes "when in its (mutant's) environment it (mutant) replaces the original" and describes how neutants perform better than the original molecule in "dissimilar environments", in environments that have changed over time and therefore require new forms - specifically new molecular structures for survival. Over time there have been generated many, many reproducing molecules that were first mutants, the "self-reproducing gigantic molecules"[219] described here:

> Step by step, matching changes in molecular structures to dissimilar environments, there have evolved some hundreds of thousands of dissimilar self-reproducing gigantic molecules. To specify a particular kind, therefore, requires a hundred thousand "yes or no" decisions - or binomial digits (we say 10^5 bits). This much information has to be transmitted from the parent molecule to its offspring with only three errors in a hundred thousand.[220]

In this theory of evolution, the specification[221] of a particular kind of molecule is required as the result of a hundred thousand binomial decisions - decisions that are made evident in the

---

[217] Ibid.

[218] Ibid.

[219] Ibid.

[220] Ibid.

[221] "To specify a particular kind, therefore, requires a hundred thousand "yes or no" decisions - or binomial digits (we say 10^5 bits)." Ibid.

structure of the molecule, such that when the neutant molecule self-reproduces, there is a transmission of information from parent molecule to offspring, such that the structure of the offspring molecule is what bears the information forward in time. This is a post-Watson and Crick accounting of the inter-generational transfer of information, where shape of a protein molecule is what bears information forward according to time and chance.

Time and chance[222] are the basis for McCulloch's concept of stability. (1) Time allows for the emergence of the molecular structures, which, in their environment, prove to be the strongest catalysts of the life reaction and (2) Chance allows for the failures, the "few times in a hundred thousand the product is discreetly different (from the original),"[223] that result in the neutant molecule. McCulloch estimates how many binomial decisions (10^5) must be transmitted every time a parent molecule regenerates itself, where binomial decisions are so many bifurcation moments in evolution encoded in the structure of the daughter molecule. As to what a binomial decision is: it is a past event in which a mutant replaces or does not replace the original. *That is the binomial decision being referred to - those decisions are not just any 0 or 1 - it's referring to the structural reality of a given molecule at a certain moment in time:* yes, this structure is a better catalyst, no, that one is not. Remember that McCulloch remains at the tiniest of scales: where physical fields - electric fields, magnetic fields, and forces still drive molecular activity. Bits are "carried in man's genes,"[224] "which are patterns of fields of these still larger molecules"[225]. I argue the "patterns of fields" refers to patterns of field *strength*; the weak field strength is what causes error, and the presence of field strength at all is what causes the molecules to be able to induce formations of other molecules of the same kind. Field strength of varying degrees would mean those autocatalytic, self-reproducing reactions exist in a gradient from more likely to less likely, contingent upon molecules' response to force, meaning that a range of molecules exist, those that are more successful at reproducing themselves and those that are less successful at reproducing themselves.

VIII. The Biological Computer

To introduce the concept of the biological computer, inheritance is figured as a hard drive: "such is the hard core of our inheritance"[226] consisting of "bits of information computed and recomputed by molecules with a mean half-life of a few hours."[227] To trace the argument from the development of McCulloch's theory of evolution, where neutant/mutant molecules that are,

---

[222] "Time and chance remove the unstable. The steps are discreet." Ibid.

[223] Ibid.

[224] Ibid.

[225] Ibid.

[226] Ibid.

[227] Ibid.

by chance, strong catalysts[228], that over time replace the original molecules, the computing and recomputing can be understood as a form of self-reproduction that ends in the process of being able to transmit information. The molecule is able to transmit information by way of its structure - not because the structure engages in an information processing reaction, but because the structure's existence is information, evidence of past success in the autocatalytic[229] and self-reproducing[230] reaction that McCulloch considers life. And as to what is stored in this "hard core of our inheritance," it is the series of binary decisions that have determined molecular structure to this point. The structures of molecules in the present whose ancestors were mutants, bear forward the binary decisions of the past as a palimpsest: they carry the history of the yes/no decisions (mutant molecule / original molecule) in their structure, as agglomerations of what structures were most efficient in the past in the catalyzing their own reproduction - any offspring molecule that is an imperfect copy of the parent molecule presents the possibility for minute alterations in future forms or versions of this molecule.[231] The reproductive molecules that together serve as the biological computer are not a considered computers for their transmission of information, they are considered computers because they are information. This, structure-based, form-based definition of computing diverges from the definition of computing offered in "Of Digital Computers called Brains." Here, a reproductive molecule is considered a computer, whereas in the earlier thought experiment, the brain is considered a computing device on account of its ability to manage electrical signals of an all-or-none value[232]. In "Biological Computers," there is a reliance on form and on the stability of a form that can be considered *digital*. Writing on stability and the absence of intermediate forms of the molecule, McCulloch presents a concept of a digital structure, a digital form that is what secures the ability of the reproductive molecule to make more copies of itself:

> How has nature stabilized this biological computer to ensure useable output? By using discreet ultimate disparate particles to make disparate atoms, by using stable disparate atoms to make discreetly dissimilar molecules. Time and chance remove the unstable. The steps are discreet. Intermediate forms or states do not exist and are so brief as to remain negligible. This we imitate in our digital computers . It is the chief source of their stability, the reason we can combine them indefinitely.[233]

---

[228] "When in its environment, it is a stronger catalyst than the original molecule. It replaces the original molecule. Such is evolution." Ibid.

[229] See quote corresponding to note 106.

[230] See quote corresponding to note 106.

[231] "This much information has to be transmitted from the parent molecule to its offspring with only three errors in one hundred thousand." Ibid.

232 "Thus, today one speaks of any de- vice for communication which performs its computations by these discrete signals indifferently as either a digital or a logical machine." McCulloch and Pfeiffer, "Of Digital Computers Called Brains," 369.

[233] McCulloch, Warren. "Biological Computers."

The biological computer refers to molecules of a particular structure or arranged in a particular formation which, because they follow discreet steps[234] (there being no 'in-between steps' in a catalytic reaction pathway) and exist in discreet forms (there being no 'in between' form between the mutant molecule and the original) are said to be the model for digital computers - McCulloch offers "*this* we imitate in our digital computers"[235], the reproductive molecules which achieve their stability by an all-or-none logic that springs from their very origin; "by using discreet ultimate disparate particles to make disparate atoms, by using stable disparate atoms to make discreetly dissimilar molecules"[236] the biological computer, the reproductive molecule made up of millions of discrete, subatomic particles, achieves stability. Because it is composed of discrete particles, it is stable and ensures a useable output which is its own self-reproduction.

The molecules of a particular structure or arranged in a particular formation referred to as the biological computer: (1) replicate themselves to create molecules or formations of molecules identical to themselves via their interactions with a pre-existing field of forces. These interactions render the molecules or formation molecules a better catalyst or not. (2) Then, the better catalysts, which are neutant-mutants of an original molecule replace the original molecule over time. (3) This replacement occurs in binary decisions that become built into the self-reproducing molecules that now exist because the self-reproducing molecules that now exist are evidence of which catalysts worked better. Evidence of the self-reproduction of the better catalysts. (4) Then the molecule self-reproduces and by way of this self-reproduction the parent molecule passes on this information to the offspring. It is not parent passes off to offspring, but molecule makes molecule, and in so doing, transmits so many accretions of past, better catalysts superseding the originals based on their environment. The question is how the molecules at the elemental level of life can produce more molecules of the same kind - "man starts life as a string of subassemblies called segments"[237] contingent upon the stability of the cell, where the origin of life arrives in the form of a catalyst, a biological computer.

The question that opened the document, "The Biological Computer," was *how does nature produce a useable output?,* for the engineer asks, "how does nature do it?"[238] And the response: the stability which allows life to reproduce itself inheres in the form of the molecule, the biological computer, which carries digital information forward on the basis of its ability to survive — to welcome — its environment. Stability is in the home, in the habit, in the ease of cloning itself, and molecules of greater complexity. The final part of this dissertation, the Coda, will address the question of stability but will scale up and will also pursue mental stability in relation to death. I will look to the leucotomy patient files of Dr. Stephen Sherwood, which include several suicides post-operation, to begin to grasp a cybernetic of the far side of life, of the impulse towards suicide.

---

[234] Discreet is McCulloch's spelling for discrete in the archival document "Biological Computers."

[235] Ibid. Emphasis my own.

[236] Ibid.

[237] Ibid.

[238] Ibid.

Conclusion

As we have demonstrated, for McCulloch the biological computer is in fact the life molecule itself, where life molecules are understood to be *reproductive* machines: "Reproductive molecules are extremely large and correspondingly complex."[239] In comparison to the unit of physics, the atomic particle, the reproductive molecule is short-lived, "its bonds are not strong enough to ensure a long mean half-life," and its activity is subject to error: "its fields are too weak to compel perfect reproduction on all occasions."And yet, nature somehow ensures a useable output from living systems. The life molecule *is* the useable output, and its source of stability is in the digital quality of its identity. The molecule is separate, discernible, discrete. Identifiable amongst others.[240]

In the molecule's very structure, it bears the history of its fitness, constituted by "a hundred thousand yes-no decisions – or binomial digits."[241] This is biological life as one type of reproducibility – and its process? The transmission of quantized information: "the steps are discrete. Intermediate forms or states do not exist and are so brief as to remain negligible."[242] The digitalization is in the form the molecule bears, and so time seems to be able to take place in the changes in form the molecule undergoes as the organism develops from embryo. For McCulloch, time is a variable of the environment, and what marks biological life from other communicative, informational processes is the irreducible peculiarity of its environment — all chemical and colloidal[243] — where the reproducibility unique to life enacts itself, "molecules determining heredity no longer reproduce except in special environments called cells." The environment where the reproduction reaction takes place, yields enzymes, substrates and their products, which serve as a dynamically stable factory, meaning that the cell understood at the level of its components possesses something automatic and as something out of time.[244] McCulloch claims the cell to be immortal, because the cell keeps going, "so long as it receives

[239] Warren McCulloch, "Biological Computers" (1957-1958) Warren S. McCulloch Papers, Box 59.

[240] Ibid.

[241] See the discussion of the gigantic biological computer and its structure: "Step by step, matching changes in molecular structures to dissimilar environments, there have evolved some hundreds of thousands of dissimilar self-reproducing gigantic molecules. To specify a particular kind, therefore, requires a hundred thousand "yes or no" decisions - or binomial digits (we say 10^5 bits). This much information has to be transmitted from the parent molecule to its offspring with only three errors in a hundred thousand." Ibid.

[242] Ibid.

[243] "We know comparatively little of the negative feedback at these chemical and colloidal levels that determine the dynamic stability of cells." Ibid.

[244] "Molecules determining heredity no longer reproduce except in special environments called cells. Within them, the reproductive reaction determines the production of other catalysts called enzymes and their products constitute a well regulated factory. The visible parts of cells, their organelles, consist of ordered molecular layers, liquid crystals, polymers and tells some of which are of remarkable fixed form outsizes and even position, while others grow, move, stretch, and divide in complicated patterns. Each of these factories is dynamically stable and so thus potentially immortal so long as it receives proper shift and energy. Yet any kind of cell would have been annihilated if, on reaching sufficient size, it did not divide into viable cells some of which reproduce again." Ibid.

proper shift and energy."[245] To me, the central concept is *time*, and specifically whether, at the level of the cell, time will degrade the cell's ability to conduct its processes. For McCulloch the central concept of the immortal cell is the electrical and chemical threshold values within the cell that will ensure its existence within a stable state:

> Up to some threshold of applied chemical, electrical, or mechanical stress, they remain in a stable state, but beyond threshold, they act suddenly differently, even though they later return to their stable state. In this they resemble the non-linear circuit elements we employ in building digital computors [sic].[246]

It is the concept of stability that allows for McCulloch's comparison of the cell to the digital computer. Not in terms of the parts, but in terms of the processes that self-regulate: the concentration of ions, the enzyme that makes too much of itself. Prior to the cell, what the *molecule* as the biological computer makes thinkable, in subsuming the environment in the same subject-position as the cell, is a concept of stability that narrates what difference there is between a cell and its environment, as ciphers and breach moments of understanding a world. It is perplexing, the explanation of morphogenesis as a factory so to accentuate the automation inherent in such a concept - and what is automated, exactly? The transformation of environment into a cell's product, the opportunity of building and responding to the world. McCulloch's study of the nervous system is a study of life, for its site is simultaneously the stimulant and receptor, the world and what might recognize it. Life is not a mere, opaque in-betweenness, some hiddenness between the molecule and its receptor, but rather it is the physical process of holding two possibilities in mind: the process of receiving the world and affecting it, the process of existing before, in time, and the process of existing in the future, in time.

He writes, "cells are inevitable."[247] Biological life and time are concepts that I believe should be considered together, and McCulloch, in his concept of *homeokinesis,* by way of the McCulloch-Pitts neuron, and with the consideration of how the brain responds to and manages perception, McCulloch gives us a *biological* method to think about time as an aspect of environment in relation to life; however, here time puzzlingly falls out of the calculus, as does the physical wear of entropy. Instead, there is no void, there is just the circuit running so consistently that time is irrelevant.

We know that for cells of the nervous system, there is, in reality, no such stability and time balloons alongside pathology. We know McCulloch and Pfeiffer accounts for this in the discussion of neurosis and Korsakow's syndrome in "Of Digital Computers Called Brains." Neurosis was attributed to circuits losing their inverse function and becoming regenerative,[248] Korsakow's to the denaturing of protein molecules engaged in the regenerative function of

---

[245] Ibid.

[246] Ibid.

[247] "Cells are inevitable - that is, they make a response which is not proportional to the stimulus." Discussion of morphogenesis and embryology of the nervous system in "Biological Computers." Ibid.

[248] Warren McCulloch and John Pfeiffer, "Of Digital Computers Called Brains," *The Scientific Monthly,* Vol. 69, No. 6. (Dec., 1949), 375.

memory.[249] The paradox of the regenerative circuit is at the heart of this dissertation: a paradox of time, circuit activity and disease, where in one direction regeneration affords an organism a past, and in the other, the loss of the organism's future. Korsakow's syndrome is discussed alongside the loss of learning resulting from alcohol as a protein denaturant[250]. McCulloch provides a neurophysiological account for *how* regenerative circuits function, as mass of cells swept into the same circuit, convulsing pathologically together as a kind of electrical cancer:

> When a circuit of this kind becomes regenerative, the regeneration tends to grow until the circuit has swept into its orbit all the cells that it can force to fire in phase. In short, its gain increases until it overloads itself maximally.[251]

In pathology, the circuit is not broken, it is redoubled. As I end the dissertation, I would like to posit that the reason for the overshadowing of the philosophy of biology of the cybernetics movement by the computer science of the cybernetics movement could be for this reason: if illness is as an intensification, a loop catching up, sparklingly, with more charge, then how to think about that quickening, life? How to think about *death* if the circuit is *inevitable*[252]*?*

In this dissertation on life, what has been absent is a consideration of death — if the nervous system sustains and begets life through a perceptual receiving and enacting of the world, whether as in an impression of the world in flesh communicated through the wires or as expression communicated through the wires reaching out to a world, then can a perceptual definition of the life of the organism be thought without a consideration of its opposite?[253]

McCulloch's papers at the American Philosophical Library include the patient files of surgeon Stephen L. Sherwood, who performed 267 leucotomy procedures at Severalls Hospital, a psychiatric hospital in Colchester England from 1940-1950.[254] Sherwood was a co-author with Warren McCulloch and Ellen Ridley on the paper "Effects of Intraventricular Acetylcholine, cholinesterase, and Related Compounds in Normal and Catatonic Cats", able to contribute to research for the paper because he was on a grant from Middlesex Hospital London to conduct

---

[249] Ibid., 372.

[250] "Moreover, clinical evidence indicates that protein denaturants destroy memory, most clearly so when alcohol, lead, or other poisons
attack an old central structure of small neurons, whose destruction produces the famous Korsakow's psychosis and makes it impossible for animals to learn." Ibid.

[251] Ibid., 375.

[252] A reference to "cells are inevitable." McCulloch, "Biological Computers."

[253] "Automata Model of Man - MESM unveiled" includes a functionalist-influenced systems approximation of marriage and why humans commune with others. He offers: "'Love' is the only thing that humanizes homo sapiens (and likely that ape-izes apes, ant-izes ants, etc.). It is the most that he can 'know.'"

[254] Behavior surgeries, Severalls Hospital. Warren S. McCulloch Papers.

research at the Department of Psychiatry, University of Illinois College of Medicine.[255] The patient files from Severalls Hospital demonstrate that Sherwood used injections discussed in these cat experiments on patients, specifically on patients with schizophrenia.

The patient files include (1) pre-operation incision sketches (2) electroencephalogram charts daily reports of individual patients residing at Severalls Hospital (3) charts comparing all leuctomy patients on the basis of the diagnosis (Affective, Schizophrenia, Dementia praecox, Involutional Psychosis, Miscellaneous, Schizo Affective Disorder), illness duration, pre-op state, operation type (MFB (medial forebrain bundle)/ CU, date of operations, age at onset, age at operation, improvement time, date admitted to hospital, date released from hospital, and final state. The "final states" listed were as follows: Family Invalid, Social Recovery, Greatly Improved, Social improvement, total recovery, transformed, 2 operations, greatly improved by injections, returned to nursing, transferred, no change, social defect, death not caused by operation, death due to operation: "The behaviors that doctors were trying to fix, they thought were set down in specific neurological connections…the idea was that if you damaged those connections, you could stop bad behaviors."[256]

To the question, *how to think of the perceptual life of the organism in relation to death?* the patient files from Severalls Hospital reveal a response in the negative — in the anonymity of the phrase "death - not caused by op." and in the particularity of "suicide" of a patient one month post-op, released on December 1951, attended with a note of "Social Recovery."[257] The particularities become more gruesome and in their unbelievability, harder to conceive of the neuronal basis, the medical basis for these patients' dying: "Lysol poisoning - suicide while on short leave"[258] and "Gassed self, carbon monoxide poisoning."[259]

Many leucotomy patients of McCulloch's collaborator, Sherwood, committed suicide, and the notion of suicide challenges much of McCulloch's epistemology. A preoccupation with an organ that provides the basis for our ability to investigate how the organ is deployed in thought is now faced with an organ that, in the wake of its own destruction under medical care, provides the basis for our ability to rid ourselves of the work of organ which would otherwise be deployed in thought. It's an involution: the brain as basis of perception which drives the discovery of ourselves and the brain as the basis of perception which drives the undoing of ourselves. For McCulloch, knowledge is the logical outcome of life, but as evidenced by his colleagues' work, in no way does knowledge secure future life.

Is suicide, then still an enactment, still a building of the world? Yes, a death that is a choice is the result of the nervous system responding to and mingling with a world. Strife lying in suicide's wake and the absence of thought is also the creation of a being for others and a being

---

[255] Detail provided in "Effects of Intraventricular Acetylcholine and Cholinesterase and Related Compounds in Normal and Catatonic cats" (1951), McCulloch Papers, Box 60, Mss.B.M139. Cf. "On a research grant from the Middlesex Hospital, London."

[256] Baron Lerner, quoted in Tanya Lewis, "Lobotomy: Definition, Procedure & History," *Live Science*. Aug 29 2014, https://www.livescience.com/42199-lobotomy-definition.html. Accessed Dec 7 2020.

[257] Behavior surgeries, Severalls Hospital, McCulloch Papers, Box 73.

[258] Causes of Death Survey, Severalls Hospital, McCulloch Papers, Box 73.

[259] Ibid.

for oneself, that one is not privy to but that one knows will be taking place. At the far end of McCulloch's medical and biological cybernetic notion of life is not merely death, but suicide. There is less a curiosity about decay than there is about anabolism, the building up of life particles from small things, but is this merely because decay is seen as inevitable due to the laws of entropy? Is it that death, in its inevitability, renders cybernetic conceptual models futile? It is less that suicide is an anathema than that it cannot be conceived of within the biological, medical cybernetics that serves as the content of this dissertation. Yet, the suicides of Severalls hospital, very much seem to be the outgrowths of a medical, biological cybernetics. The self-regulating system would never choose to nullify its existence by undoing itself. Suicide is McCulloch's cratering Mars[260], a field that *could* make the criteria for biological life more apparent given the absence of explicability of suicide.

In this dissertation, in discussions of environment, information and the laws of physics that serve as natural law, life occurs in time in relation to an abundant world. In Catherine Malabou's *The New Wounded*, the brain injury, the lesion is not dissimilar from the injuries suffered by those treated with leucotomy, that has "loss as its premise."[261] As Malabou argues:

> Lesional plasticity thus reveals a strange sculptural power that produces form through the annihilation of form. To the extent that neurological patients have suffered, to different degrees, disturbances in their inductors of emotion, their new identities of neurological patients are characterized by disaffection or coolness. A bottomless absence.[262]

Form, in the shape of a molecule and expressed through the enactment of physical laws, is what lies against "a bottomless absence." Its presence, borne from its activity, is information in the void, and – in cybernetic terms – is the very origin of *life*.

---

[260] See discussion of McCulloch and Brodey's conception of what it would mean to detect life on Mars in Chapter 3 of this dissertation. Detecting life on Mars is discussed in their "The Biological Sciences," Robert Hutchins and Mortimer Adler, eds., *The Great Ideas Today, 1966* (Chicago: Encyclopedia Brittanica Inc, 1966): 288-334; quote p. 292.

[261] Catherine Malabou,. *The New Wounded: From Neurosis to Brain Damage,* trans. Steven Miller (New York: Fordham University Press, 2012), 48.

[262] Ibid.

References

Unpublished material

The Warren S. McCulloch Papers, American Philosophical Society Library. Philadelphia, PA.

Conversations

Chair, David Bates

Gaetan Micco

Works Cited

Abraham, Tara. "(Physio)logical Circuits: The Intellectual Origins of the McCulloch-Pitts Neural Networks." Journal of the History of the Behavioral Sciences 38, no. 1 (2002): 3-25.

Abraham, Tara. Rebel Genius: Warren S. McCulloch's Transdisciplinary Life in Science. MIT, 2016.

Apter, Julia. "Projection of the retina on superior colliculus of cats." Journal of Neurophysiology. 1945 8:2, pp. 123-134.

Asylum Projects. "Manteno State Hospital." May 22, 2020. Accessed Dec. 3, 2020. <https://www.asylumprojects.org/index.php/Manteno_State_Hospital>.

Bates, David. "Automaticity, Plasticity, and the Deviant Origins of Artificial Intelligence." David Bates and N. Bassiri, eds. Plasticity and Pathology: On the formation of the neural subject. Fordham University Press: New York, 2016. pp. 194-218.

Behavior surgeries, Severalls Hospital. 1940-1959. Box 73. Warren S. McCulloch Papers. American Philosophical Society Library. Philadelphia, PA. Jan. 6, 2020.

Belliveau AP, Somani AN, Dossani RH. "Pupillary Light Reflex." StatPearls. StatPearls Publishing, 2020. Updated Jul 31 2020. <https://www.ncbi.nlm.nih.gov/books/NBK537180/>. Accessed Dec 8 2020.

Canguilhem, Georges. "Machine and Organism." Trans. Mark Cohen and Randall Cherry. Incorporations. Edited by Jonathan Crary and Sanford Kwinter. Zone, 1992. Pp 44-69.

Canguilhem, Georges. The Normal and the Pathological. Trans. Carolyn Fawcett. Zone Books, 1989.

Cannon, W. B. “Organization for physiological homeostasis.” Physiological Review. 9: 399-431, 1929.

Causes of Death Survey, Severalls Hospital.1940-1959. Box 73. Warren S. McCulloch Papers. American Philosophical Society Library. Philadelphia, PA. Jan. 6, 2020.

Chattopadhyay D. and P.C. Rakshit. Electronics: Fundamentals and Applications. New Age International Publishers, 2006.

Connors, M. F., B. W., & Paradiso, M. A. Neuroscience: Exploring the brain (4th ed.) Lippincott Williams and Wilkins, 2016. Kindle Edition.

Dumit, Joseph. Picturing Personhood: Brain Scans and Biomedical Identity. Princeton University Press : Princeton, 2004.

Dupuy, Jean-Pierre. On the Origins of Cognitive Science: The Mechanization of the Mind. Trans. M.B. DeBevoise. Princeton University Press, 2000.

The Editors of Encyclopaedia Britannica. “Sir Hermann Bondi”. Encyclopædia Britannica. October 28, 2020 <https://www.britannica.com/biography/Hermann-Bondi>. November 03, 2020.

Edwards, Paul. The Closed World: Computers and the Politics of Discourse in Cold War America. MIT Press, 1997.

Fischer, Martin. The Physiology of Alimentation. John Wiley & Sons, 1911.

von Foerster, Heinz, Margaret Mead, and Hans Lukas Teuber. “A Note by the Editors.” Cybernetics: The Macy Conferences - 1946-1953. Claus Pias, Ed. diaphanes, 2016. pp 341-348.

Gerard, Ralph. “Some of the Problems Concerning Digital Notions in the Central Nervous System.” Cybernetics: The Macy Conferences 1946-1953. Claus Pias, Ed. diaphanes, 2016. pp. 171-202.

Geroulanos, Stefanos and Todd Meyers. The Human Body in the Age of Catastrophe: Brittleness, Integration, Science and the Great War. University of Chicago Press, 2018.

Goldstein A. “The Mechanism of Enzyme-Inhibitor-Substrate Reactions: Illustrated by the Cholinesterase-Physostigmine-Acetylcholine System.” Journal of General Physiology. 1944;27(6):529–580.

Hayles, Katherine. N. How we became Posthuman: virtual bodies in literature, cybernetics and i informatics. University of Chicago, 1999.

Heidegger, Martin. Being and Time. Trans. John Macquarrie and Edward Robinson. Harper Perennial Modern Thought, 2008.

Heims, Steve. The Cybernetics Group. MIT, 1991.

Helmenstine, Anne Marie. “Fluorescence Versus Phosphorescence.” ThoughtCo. June 02 2019. Accessed Nov. 18 2020. <https://www.thoughtco.com/fluorescence-versus phosphorescence-4063769phosphorescence-4063769>.

James, William. The Varieties Of Religious Experience: A Study In Human Nature. Seven Treasures, 2009.

Kant, Immanuel, and Werner S. Pluhar (trans.) Critique of Judgment. Hackett Pub. Co., 1987.

Kaufman, Sharon. Ordinary Medicine: Extraordinary Treatments, Longer Lives, and Where to Draw the Line. Duke University Press, 2015.

Kay, Lily. Who Wrote the Book of Life?: A History of the Genetic Code. Stanford University Press, 2000.

Keller, Evelyn Fox. Refiguring Life: Metaphors of Twentieth Century Biology. Columbia University Press, 1996.

Kitzinger, Helen, Devere G. Arnold, Robert W. Cartwright & David Shapiro. “A Preliminary Study of the Effects of Glutamic Acid on Catatonic Schizophrenics.” Rorschach Research Exchange and Journal of Projective Techniques, 1949, 13:2, 210-218.

Kleen, Michael. Haunting the Prairie: A Tourists Guide to the Weird and Wild Places of Illinois. Black Oak Press, 2010.

Kline, Ronald. The Cybernetics Moment, or Why We Call Our Age the Information Age. John Hopkins University Press, 2015.

Lashley, K.S. The Mechanism of Vision: XV. Preliminary Studies of the Rat's Capacity for Detail Vision, The Journal of General Psychology, 18:1, 1938. pp. 123-193.

Lettvin, Jerome. “Introduction to Volume I.” Collected Works of Warren S. McCulloch, by Warren S. McCulloch et al., Intersystems Publications, 1989, v1. pp. 7-20.

Lewis, Tanya. “Lobotomy: Definition, Procedure & History.” Live Science. Aug 29 2014 < https://www.livescience.com/42199-lobotomy-definition.html >. Accessed Dec 7 2020.

LibreTexts. “1.2: Atomic Structure - Orbitals”. Chemistry. October 15 2020. Accessed Dec. 3 2020 <https://chem.libretexts.org/Bookshelves/Organic_Chemistry/Map%3A_Organic_Chemistry_(McMurry)/01%3A_Structure_and_Bonding/1.03%3A_Atomic_Structure_-_Orbitals>.

Lindsay, J. S. Bonar. “Periodic Catatonia.” Journal of Mental Science, vol. 94, no. 396, 1948, pp. 590–602.

Logue, A.W. . The Psychology of Eating and Drinking. Freeman, 1991.

Malabou, Catherine. The New Wounded: From Neurosis to Brain Damage. Trans. Steven Miller. Fordham University Press, 2012.

Malabou, Catherine. What Should We Do with Our Brain? Trans. Sebastian Rand. Fordham University Press, 2008.

Marx, Karl. Capital, a critique of political economy, vol. 1. Trans. Ben Fowkes. Vintage Books, 1977.

McCulloch, Rook. “Foreword” Collected Works of Warren S. McCulloch, by Warren S. McCulloch et al., Intersystems Publications, 1989, v1. pp. 1-6.

McCulloch, Warren S. “Automata Model of Man - MESM unveiled”. 1967. Box 58. Mss.B.M139. The Warren S. McCulloch Papers at the American Philosophical Society Library. Philadelphia, PA. 10 Jan. 2020.

McCulloch, Warren S. “Aviation in Medicine”. 1945. Box 58. Mss.B.M139. The Warren S. McCulloch Papers at the American Philosophical Society Library. Philadelphia, PA. 10 Jan. 2020.

McCulloch, Warren. “Biological Computers.” 1957-1958. Box 59. Mss.B.M139Warren S. McCulloch Papers. American Philosophical Society Library. Philadelphia, PA. Jan. 10, 2020.

McCulloch, Warren. “Recollections of the Many sources of Cybernetics”. Collected Works of Warren S. McCulloch, by Warren S. McCulloch et al., Intersystems Publications, 1989, v1. pp. 21-49.

McCulloch, Warren, Ellen Ridley, Isiah Share and John Berry. “Dog’s Blood-sugar level affected by Taste and Sham-feeding.” 1951-1952. Box 60. Mss.B.M139. Warren S. McCulloch Papers. American Philosophical Society Library. Philadelphia, PA. July 30, 2018.

McCulloch, Warren, Ellen Ridley and Stephen Sherwood. “Effects of Intraventricular Acetylcholine and Cholinesterase and Related Compounds in Normal and Catatonic cats.” 1951. Box 60. Mss.B.M139. Warren S. McCulloch Papers. American Philosophical Society Library. Philadelphia, PA. July 30, 2018.

McCulloch, Warren and John Pfeiffer. “Of Digital Computers Called Brains.” The Scientific Monthly, Vol. 69, No. 6. (Dec., 1949). JSTOR 01 04 2019.

McCulloch, Warren and Walter Pitts. “A Logical Calculus of the Ideas Immanent in Nervous Activity.” Collected Works of Warren S. McCulloch, by Warren S. McCulloch et al., Intersystems Publications, 1989, v1. pp. 343-361.

McCulloch, Warren and Warren Brodey. “The Biological Sciences”. The Great Ideas Today, 1966. Edited by Robert Hutchins and Mortimer Adler. Encyclopedia Brittanica Inc, 1966. 288-334.

McLuhan, Marshall. Understanding Media: The Extensions of Man. Penguin, 1966.

Morozov, Evgeny. 2018. “‘A Bath of Continuous Sensations’: Warren Brodey’s Quest for Human Augmentation and Intelligent Environments, 1955-1975”. Doctoral dissertation, Harvard University, Graduate School of Arts & Sciences.

Noë, Alva. Strange Tools: Art and Human Nature. Farrar, Straus and Giroux, 2015.

Pias, Claus. “The Age of Cybernetics”. Cybernetics: The Macy Conferences 1946-1953. Claus Pias, Ed. diaphanes, 2016. pp. 12-26.

Pressman, Jack. The Last Resort: Psychosurgery and the History of Medicine. Cambridge University Press, 2002.

Richmond, J.F. . New York and Its Institutions, 1609-1871. W.T. Keener, 1871. Accessed Dec. 1 2020<https://archive.org/details/newyorkanditsin03richgoog>.

Rilke, Rainer Maria. “The Tao that can be Named.” The Inner Sky: Poems, Notes, Dreams by Rainer Maria Rilke. Trans. Damion Searls. David R. Godine, 2010.

Schaffner J.S. “Almost Sinusoidal oscillations in non-linear systems.” University of Illinois Engineering Experiment Station. Bulletin Series No. 421.1950. University of Illinois at Urbana-Champaign Library. Accessed Dec 3 2020 <https://www.ideals.illinois.edu/bitstream/handle/2142/4369/engineeringexperv00000i00421.pdf?sequence=3&isAllowed=y>.

Schubert, Mitchell L. “Chapter 47-Regulation of Gastric Acid Secretion.” Physiology of the Gastrointestinal Tract (Fifth Edition). Leonard R. Johnson, Fayez K. Ghishan, Jonathan D. Kaunitz, Juanita L. Merchant, Hamid M. Said, Jackie D. Wood, Eds. Academic Press, 2012.

Science in the City. “Smoke Rings – Air Vortex Movements.” Stanford University. 2020. <https://scienceinthecity.stanford.edu/resources/smoke-rings-air-vortex-movements/ >. Accessed. Dec 8 2020.

Share, Isiah, Eugene Martyniuk and M.I. Grossman. “Effect of Prolonged Intragastric Feeding on Oral Food Intake in Dogs,” 1952. Box 60. Mss.B.M139. Warren S. McCulloch Papers. American Philosophical Society Library. Philadelphia, PA. July 30, 2018.

Smith, John. The Palgrave MacMillan Psychology of Food and Eating: A Fresh Approach to Theory and Method. Palgrave MacMillan, 2002.

Stiegler, Bernard. Technics and Time, 1: The Fault of Epimetheus. Trans. Richard Beardsworth and George Collins. Stanford, 1998.

Todman, D. “Henry Dale and the Discovery of Chemical Synaptic Transmission.” European Neurology 2008;60:162-164.

Thom, René. Structural Stability and Morphogenesis; an Outline of a General Theory of Models. [1st English ed.], W. A. Benjamin, 1975. EBSCOhost, search.ebscohost.com/login.aspx?direct=true&db=cat04202a&AN=ucb.b14022972&site=eds-live.

Turing, Alan. “Intelligent Machinery.” The Essential Turing: the Ideas that gave birth to the Computer Age. Ed. B. Jack Copeland. Oxford University Press, 2004. pp. 395-432.

Typewritten note accompanying “Effects of Intraventricular Acetylcholine and Cholinesterase and Related Compounds in Normal and Catatonic Cats” drafts. 1951. Box 60. Mss.B.M139. Warren S. McCulloch Papers. American Philosophical Society Library. Philadelphia, PA. July 30, 2018.

U.S. Army Harry Diamond Laboratories. “Proceedings of the Timers for Ordnance Symposium, Volume 2.” U.S. Army Materiel Command, Harry Diamond Laboratories, 1966.

Vidal, Fernando. Being Brains: Making the Cerebral Subject. Fordham University Press, 2017.

Wiener, Norbert. Cybernetics: Or the Control and Communication in the Animal and the Machine. 2nd edition. Quid Pro, 2013.

Wiener, Norbert. Cybernetics, or Control and Communication in the Animal and the Machine. MIT, 1948.