Foreword

Early in the 19th century debates on Darwinian theory of evolution, William James asked the question whether consciousness had biological survival value, such that it might be subject to natural selection. The alternatives he considered were widely held notions that consciousness was either an epiphenomenon or a celestial gift of the capacity to conceive and know a Creator. He answered in fluid Victorian prose:

*A priori* analysis of both brain and conscious action shows us that if the latter were efficacious it would, by its selective emphasis, make amends for the indeterminacy of the former; whilst the study *à posteriori* of the distribution of consciousness shows it to be exactly such as we might expect in an organ added for the sake of steering a nervous system grown too complex to regulate itself.1

In raising and answering the question this way, James penetrated to the essential role of the brain in behavior. The brain simplifies. We and other animals cannot fully know the world, Kant’s *Ding an sich*, as it is in its infinite complexity. Instead, we make finite educated guesses about the world that Kant called “categories” and that we now call “representations” or “world models”. We test these hypotheses by taking action into the world and refining our guesses into formal theories. We learn to know our world by accommodating and adapting to the sensory consequences of our own and others’ actions through trial-and-error reinforcement learning [Freeman (2001)].2 Thereby we achieve the simplicity that makes it possible for each of us, immersed in a sea of uncertainty, to take effective action lit by flashes of insight.

Neurodynamicists model this self-organized, self-educating process by constructing mathematical descriptions of the motor systems that thrust the body into and through the world. They postulate that the sensory systems maintain attractor landscapes that are constructed by Hebbian and other forms of synaptic modification in cortical networks, which are the structural repository of experience. Each act of observation is a test of the world, and the multiple attractors are predictions of possible outcomes of the test, giving evidence for sustenance, companionship, danger,

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1 See p. 18 of James, W: Are we automata? Mind 4, 1–21 (1879)
nothing new, or something novel. The basins of attraction are generalization gradi-
ents from prior receptions of stimuli. A stimulus places cortical dynamics in one of
the basins of attraction. Convergence to an attractor is an inductive generalization by
which the stimulus is categorized. The attractor manifests a spatiotemporal pattern
of neural activity to which the cortical trajectory converges [see Chaps 1, 2, 7 of this
book; also Freeman (2001)], and which the sensory cortex transmits to its targets by
well-known networks and pathways [Chap. 5 of this book].

Here is the crux of perception. The sensory input is a representation of the stim-
ulus; the cortical output is not. Based on the memories of the stimulus, the output
is the mobilized knowledge about the meaning of the stimulus [Freeman (2001)].
The experience is familiar to everyone; a whiff of perfume, a few notes of a tune,
or a glimpse of a face can trigger a cascade of recollection and emotion. Whereas
the pattern of the sensory-driven cortical activity is defined by the parameters of
the physical world, and by the neural operations of the sensory systems, the self-
organized pattern of cortical activity is defined by the modified synapses that store
the accumulated experience of the perceiver [Chap. 11]. Hence the critical event
in each act of perception is the reorganization of a stimulus-driven activity pattern
in cortex, which embodies the unique and unknowable impact from the world into
an endogenous pattern of self-organized activity. The neurons are the same; their
anatomical connections are the same; even their level of energy may be the same;
what differs is the spatiotemporal organization of their interactions.

The process of sudden reorganization of neural masses in the brain is the subject
matter of this book. It is the phase transition [Freeman (1999)]\(^3\) that is modeled
by use of differential equations [Chap. 8; Freeman and Vitiello (2006)]\(^4\) or random
graph theory [Chap. 5; neuropercolation, Kozma et al. (2005)].\(^5\) In its simplest form
it is the succinct, localized transition in the state of a sensory cortex from a receiving
state to a transmitting state. Cortex transforms a recept into a percept by constructing
knowledge from information. That is the first step in the transition by the brain from
an expectant state to a knowing state, the elusive “Aha!” experience. It is also the
transition from body into mind, from a pattern determined by the physics of matter
in the world to a self-organized pattern that exists only in the perceiver as a mental
state. Abrupt global reorganizations by phase transitions in larger brain systems
implement a wide variety of intellectual and intentional brain functions, ranging
from simple go/no-go choices, switching from rest to action and back [Chap. 4],
from prodrome to epilepsy [Chaps 2, 5], from sleep to wake or REM [Chap. 9], and,
far beyond our current reach, from Heidegger’s thrownness in childhood through

\(^3\) Freeman, W.J.: Noise-induced first-order phase transitions in chaotic brain activity. Internat. J.

\(^4\) Freeman, W.J., Vitiello, G.: Nonlinear brain dynamics as macroscopic manifestation of underly-
ing many-body field dynamics. Physics of Life Reviews 3, 93–118 (2006),

\(^5\) Kozma, R., Puljic, M., Balister, P., Bollabás, B., Freeman, W.J.: Phase transitions in the neurop-
92, 367–379 (2005), http://repositories.cdlib.org/postprints/999
adolescence to mid-life crises, military, religious or political conversions, and all other forms of social bonding.

Physicists and engineers are familiar with state changes, charting them as discontinuities in trajectories of state variables through state space. Neurologists and psychiatrists well understand states of mind and altered states of consciousness. What is to be gained by calling brain states “phases”, which gives the title of this book?

On its face the usage appears to be no more than a treacherous analogy. On the one hand the classical thermodynamic definition holds for closed systems at equilibrium, whereas brains are open, dissipative systems operating far from equilibrium. The classical phases and their boundaries are unequivocally defined in terms of temperature and pressure, whereas brains homeostatically regulate temperature, pressure, volume, and mass. Conventional phase transitions involve latent heat, so that the Ehrenfest classification by discontinuities of derivatives has been largely discarded by physicists, but as yet no comparable transition energies have been seen or postulated in cortical phase transitions, so discontinuities must suffice for neurodynamists.

On the other hand, the several fields of condensed-matter physics have evolved in diverse directions such as nonequilibrium thermodynamics, ferromagnetics, optics, and computational fluid dynamics, but with commonality in important aspects [Schroeder (1991)]. Phase now is defined as a state of aggregation of particles [Schwabl (2006)], whether they are atoms, molecules or neurons. In each complex system there are multiple types of state. In the brain, families of attractor landscapes in sensory cortical dynamics define the phase space [Freeman and Vitiello (2006)]. In each aggregate there are certain conditions that specify a critical point in the phase space at which the system is particularly susceptible to transit from one phase to another phase [Chap. 1]. The transition involves a change in the degree of order, as when the neurons in sensory cortex transit from a disorganized state of expectancy to an organized state of categorization, from noise to signal, from the symmetry of uniformity of the background activity at rest to the asymmetry of spatiotemporal structure in action. This is symmetry breaking, which is described using bifurcation theory [Chaps 1, 10, 11].

Most importantly, the order emerges by spontaneous symmetry breaking within and among populations of cortical neurons. Order in the form of gamma synchrony [Chaps 7, 8, 11, 12] is not imposed by sensory receptors or pacemaker neurons. It is constructed by broadly distributed synaptic interactions by which neurons constrain or “enslave” themselves and each other in circular causality [Haken (1983)]. Modeling symmetry breaking requires the introduction of an extra variable, an order parameter [Chap. 3], which serves to evaluate the strength of interaction by which

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the order is achieved [Sethna (2009)]. The variable must be evaluated by measuring the summed activity of the aggregate, minimally from practical experience on the order of 10,000 neurons [Freeman, (2001)]. The mesoscopic order [Chap. 7] is undefined in microscopic activity, in much the way that molecules do not have pressure and temperature. Furthermore, it is undetectable in microelectrode recordings of action potentials except by prolonged time-averaging in histograms, which precludes measuring rapid changes in the degrees of freedom or patterns of order. Herein lies the value of the dendritic potentials recorded from cortex extracellularly and referentially in various forms of electroencephalogram (EEG) and local field potentials [Chaps 1, 6, 8, 11], which are averages of potential fields from local neighborhoods of neural populations. The EEG order parameter (derived from field potential measurements) is not the order, nor is it the agency of the order; it is an index of the distributed, self-organized and self-organizing interaction strength among the neurons.

The perceptual phase transition is many-to-one by convergence to an attractor, so it is irreversible, non-Abelian and non-commutative with no inverse. Unlike the holographic transformation, which is information-preserving and non-categorizing, the phase transition destroys information in categorizing as the prelude to decision-making. To these properties are added the characteristic amplification and slowing of fluctuations as criticality is approached [Chaps 1, 8]; the emergence of power-law distributions of spectral energy and functional connectivity [Chaps 1, 3, 4, 8]; long correlation lengths reflecting emergence of truly immense domains [Freeman (2003)] of coherent gamma oscillations; and reorganization/resynchronization of phase and amplitude modulations of the transmission frequencies at rates in the theta and alpha ranges [Freeman (2009)].

Perhaps the most compelling reason to model the dynamics of perception as a phase transition is the reduction in degrees of freedom owing to augmented interaction [Freeman and Vitiello (2006)], which resembles the increase in density as gas condenses to liquid. The condensation of neural activity is manifested in the long-range spatiotemporal coherence of gamma oscillations (Chaps 1, 4, 12), and the conic phase gradients resembling vortices that accompany the EEG amplitude patterns that are correlated with behavior [Freeman (2001)]. The phase transition begins at a singularity (Chaps 1, 8), which in cortex is demarcated spatially by the

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apex of the cone. It is marked temporally by a downward spike in power in the pass band of the transmission frequency [Freeman (2009)].

Given these properties in brain dynamics, the analogy is exceedingly attractive and likely to persist and grow, because it provides matrices of educated guesses by which further progress can be made in making sense of diverse data. The phase transition establishes a link between energy and order. Brains are profligate in the dissipation of metabolic energy, yet by their own feedback controls they keep constant a vast reservoir of electrochemical energy in the ionic concentration gradients that empower the neural activity of the brain. The major thermodynamic variables are in steady state, owing to provision by arterial blood flow of free energy and the disposal by the venous blood flow of waste heat, except one: there is a continual decrease in entropy [Chap. 4], which is paid for by the throughput of energy. Initially the patterns are solely functional, the creation of chaotic dynamics. Owing to the plasticity of cortical connectivity [Chaps 2, 4, 7, 9, 11] the functional patterns guide the structural connectivity into more or less permanent brain patterns, which constitute the neural foundation for long-term memory.

Despite these properties and the powerful tools used to derive and describe them, the hypothesis that phase transitions underlie perception and other brain functions remains unproven. Asserting it is like signing a promissory note. There are immediate intellectual gains from access to the capital of others’ ideas, but they bring unsolved problems, salient among them defining the relation between metabolic brain energy and neural activity, in which both excitation and inhibition dissipate energy. The debt will not be paid until a detailed theory of nonlinear neurodynamics is constructed that can stand on its own, in company with other major branches of physics devoted to the study of condensed matter. Considering the saliency of its subject matter, a successful theory of neurodynamics is likely to outshine all others.

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