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How and Why Brains Create Meaning from Sensory Information

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Abstract

Semantics is the essence of human communication. It concerns the manufacture and use of symbols as representations to exchange meanings. Information technology is faced with the problem of using intelligent machines as intermediaries for interpersonal communication. The problem of designing such semantic machines has been intractable because brains and machines work on very different principles. Machines process information that is fed to them. Brains construct hypotheses and test them by acting and sensing. Brains do not process information because the intake through the senses is infinite. Brains sample information, hold it briefly, construct meaning, and then discard the information. A solution to the problem of communication with machines is to simulate how brains create meaning and express it as information by making a symbol to represent the meaning to another brain in pairwise communication. An understanding of the neurodynamics by which brains create meaning and represent it may enable engineers to build devices with which they can communicate pairwise, as they do now with colleagues.

1. Introduction

The most challenging of the three branches of semiotics is called semantics [Freeman, 2000b]. It deals with the relation between meanings and representations, a relation often referred to in artificial intelligence and philosophy as 'intention', 'aboutness' (a thought, belief or memory is 'about' something), or 'symbol grounding'.

Computers are very good in the other two branches: syntactics (the relation of symbol to symbol as found in dictionaries) and pragmatics (the relations between symbol and action like those of traffic signals). They are inept in semantics. The reason for this ineptitude stems from deep differences between brains and computers, as von Neumann [1958] surmised nearly half a century ago:

"We have now accumulated sufficient evidence to see that whatever language the central nervous system is using, it is characterized by less logical and arithmetic depth than we are normally used to. ... Thus the outward forms of our mathematics are not absolutely relevant from the point of view of evaluating what the mathematical or logical language truly used by the central nervous system is. [W]hatever the system is, it cannot fail to differ considerably from what we consciously and explicitly consider as mathematics. p. 81"

It would appear from his actions that Alan Turing [Millican & Clark, 1996] encountered this impasse earlier in the same decade. Having pioneered in the development of the universal machine that bears his name, he left the field of artificial logic and invented the entirely different field of chemical morphogenesis [Turing, 1952]. Here he put to use his mathematical logic for the description of the emergence and evolution of spatiotemporal patterns in chemical and biological systems. The possibility was precluded by his tragic early death that he might have put into service these novel insights by devising machines that he could evaluate with his Turing test for intelligence. We can surmise that he already saw the limits of computation as a model for biological intelligence. His successors in AI have used his test to evaluate systems that manipulate symbols syntactically, but with few exceptions, such as Grey Walter [1953], Ross Ashby [1952], Andy Clark [1996] and Horst Hendriks-Jansen [1996], they have not adequately explored dynamical devices that prowl their environments to create semantic knowledge about their worlds by their own actions.

Brains are exceedingly capable of grasping the salient features of complex situations and social relationships, which are captured in such words as 'value', 'significance', 'import', or 'bottom line', in a word, 'meaning'. It is my conclusion in this essay that meanings exist only in brains, where they take the place of the internal representations that computers use. My conclusion is based on research into the spatiotemporal patterns of active states of

brains in animals, that accompany and support the animals' performance of the cognitive tasks involved in learning to respond appropriately to simple stimuli that signify events and circumstances that are vital to their welfare. I find that sensory cortices receive the information that the sensory receptors provide from stimuli, and that this information, once it has arrived in cortex, triggers the construction of activity patterns in brains that constitute the meaning of the stimuli. These patterns over-ride the sensory-driven information [Freeman, 1999], which is then discarded, so that everything that an animal learns about its environment has been constructed within its brain by processes of abstraction and generalization.

In order to translate these findings into terms that engineers will require to emulate in hardware the performance of brains in wetware, some further consideration of the biological basis of meaning is required. A meaning state is an active state that occupies the entire available brain [Freeman, 1999]. The construction begins with formation within the brain of a pattern of neural activity that embodies its immediate goal, such as food, shelter or a mate, the achievement of which requires acquisition of information from the environment. That information is got by intentional action into the environment, followed by sensory stimulation and learning from consequences of the action. A stimulus such as a light, an odor, or a tone contains information that serves to represent to the animal the state of its environment. It is a material object or process that is equivalent to a book, face, or gesture for humans. It is a part of the environment that has no meaning in itself. The French poet Paul Valéry [1957] wrote:

"I have already explained what I think of literal representation; but one cannot insist enough on this: there is no true meaning of a text.□ No author's authority.□ Whatever he may have wanted to say, he wrote what he wrote.□ Once published, a text is like an implement that everyone can use as he chooses and according to his means: it is not certain that the maker could use it better than someone else."

My analysis of brain activity patterns shows that sensory cortical activity patterns that are triggered by stimuli are selected by the stimuli but are determined by the history and context of the relations of the individual to the stimuli [Freeman, 1999, 2000a]. These brain activity patterns are states of meaning. They occur in the dynamic state space of a brain [Basar, this volume; Wright et al., this volume] as trajectories of discrete steps marked by cortical phase transitions [beim Graben, Saddy & Frisch, this volume]. The patterned active states are called wave packets [Freeman, 1975]. The way in which they are made by the self-organizing brain dynamics that controls behavior is a pivotal topic in this essay.

The dynamics of brains that creates meaning can be emulated in computer models of brain function [Freeman et al., 1997; Kozma & Freeman, 2001] and analog hardware [Eisenberg, Freeman & Burke, 1989; Principe et al., 2001]. However, this step requires that a major problem be addressed: the relation between representation and meaning in brain function. The Shannon-Weaver information theory is representational, so it divorces meaning from information and therefore does not apply directly to brains. Shannon [1948] wrote:

"The fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point. Frequently the messages have meaning; that is they refer to or are correlated according to some system with certain physical or conceptual entities. These semantic aspects of communication are irrelevant to the engineering problem".

Section 2 sketches some of the principal elements of communication, as a basis for discussing a pathway toward solutions through a better understanding of the biological basis of meanings, which grow from behavioral actions, not from the rule-driven operations between symbols embedded within syntactical systems such as computers, nor from conventional 'computing with words'. Section 3 summarizes the main observations on sensory cortical wave

packets. Section 4 enlarges the description to include the limbic system and the origin of intentional behavior. Section 5 takes up the critical difference between linear and circular causality that underlies the distinction between deterministic and self-organizing systems. Section 6 discusses in more detail the relations between meaning and representation. Section 7 summarizes.

2. Communication by representations

Operational discreteness is essential for communication in dialogue. A pair of brains can act, sense, and construct in alternation with respect to each other, just as dogs sniff, and as two humans plan, speak, listen, and hear. Consider brains **A** and **B** interacting [Figure 1], where **A-B** are parent-child, wife-husband, rabbit-dog, philosopher-biologist, neuroscientist -rabbit, etc. **A** has a thought that constitutes some meaning $M(a)$. In accordance with this meaning **A** acts to shape a bit of matter in the world (a trace of ink on paper, a vibration of air, a set of keystrokes on e-mail, movements of the face, etc.) to create a representation (a sign or symbol for humans, merely a sign for animals, in both cases, information) directed at **B**, $R(a)$. **B** is impacted by this shaped matter and is induced by thought to create a meaning $M(b)$. So **B** acts to shape a bit of matter in accordance with $M(b)$ in a representation $R(b)$, which impacts on **A** to induce $M(a+1)$.

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Figure 1 near here

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And so on. Already by this description there is implicit recognition of a discrete recurrent flow of conversation like the tides, so that meanings $M(i)$'s as constructions of thoughts become the internal active states, and the $R(i)$'s as attributes of matter become the external representations. The interchange requires a coordinated succession of phase transitions in both communicants. By its relatively fixed nature an external "representation can be used over and over, just as we use a letter, word, ideograph or equation. It cannot be said to contain or carry meaning, since the meanings are located uniquely inside **A** and **B** and not between them. The same **R** induces different

meanings $M(i)$ in any other subject C who may intercept the transmission of a representation. The objects that are used to communicate are shaped by meanings that are constructed in A and B iteratively, and they induce the constructions of meaning in B and A alternately. If communication is successful, then the internal meanings will come transiently into harmony, as manifested by cooperative behavior such as dancing, walking in step, shaking hands, exchanging notes, ringing bells, etc. Symbols persist in books and stone tablets, while minds fluctuate and evolve until they die.

3. Observations of the electroencephalogram (EEG)

A biological approach to the problem of meaning is to study the evolution of minds and brains, on the premise that animals have minds that are prototypic of our own, and that their brains and behaviors tell us what essential properties are common to animal and human minds. Experimental measurements of brain activity manifested in the electroencephalogram (EEG) recorded intracranially have shown that following sensory stimulation, the sensory cortices engage in construction of activity patterns that incorporate the stimuli [Freeman, 1999; Ohl, Scheich & Freeman, 2001]. The operations are not those that are characteristic of computers, which include filtering, storing, retrieval, gradient descent, or correlation mechanisms. Each construction is by a phase transition, in which a sensory cortex switches abruptly from one basin of attraction to another, thereby changing one spatial pattern instantly to another like successive frames in a cinema. The transitions in the primary sensory cortices (visual, auditory, somatic and olfactory [Barrie, Freeman & Lenhart, 1996]) are shaped by interactions with the limbic system, which establish multimodal unity, selective attention, and the intentionality of percepts. The interactions of the several sensory cortices and the limbic system lead to goal-directed actions in time and space. Each cortical phase transition involves synaptic changes constituting learning throughout the forebrain, so that cumulatively a unified and global trajectory is formed by each brain over its lifetime. Each spatial pattern appears to

reflect the entire content of past and present experience [Skarda & Freeman, 1987], that is, a meaning.

Studies of EEG recorded extracranially on the scalp of humans have given different perspectives on the same neurodynamics of perception. Interest has been focused on the gamma range of the EEG temporal spectrum (20 - 80 Hz in rabbits), for which there is now substantial evidence for episodic, widespread coherence [Nunez et al., 1997; Srinivasan, this volume] of gamma oscillations in relation to cognitive behavior in conjunction with semantic stimuli [von Stein et al., 1999], with the Stroop task [Schack et al. 1999; Schack this volume], with visual stimuli [Miltner et al., 1999; Rodriguez et al., 1999; Müller et al., 1996; Müller, 2000; Haig et al., 2000], in a pattern recognition task by infants [Csibra et al., 2000], in a delayed response memory task by adults [Tallon-Baudry et al., 1996, 1998], and in professional musicians listening to music [Bhattacharya, Petsche & Pereda, 2001]. Emphasis has usually been placed on thalamocortical feedback relations [Petsche, 1996; Liley et al., 1999; Taylor, 1997; Slotnick et al., 2002; Kraut et al., 2002], though the oscillations are also found in the olfactory system that do not depend on thalamic input for their genesis [Freeman, 1975].

The most important experimental finding in the animal studies is that the neuroactivity patterns in sensory cortex, which form during perception of conditioned stimuli by the animals, are not invariant with respect to unchanging physicochemical stimuli. The brain activity patterns are found to change slightly and cumulatively with any change in the significance of the stimuli, such as by changing the reinforcement, or with the addition of new stimuli [Freeman, 1992]. From numerous tests of this kind the conclusion is drawn that brain patterns reflect the value and significance of the stimuli for the animals, not fixed memory traces. Each pattern forming in response to the presentation of a stimulus is freshly constructed by chaotic dynamics in the sensory cortex, in cooperation with input from the limbic system that implements the supporting processes of attention and

intention, and it expresses the history and existing state of the animal rather than the actual incident stimulus. The patterns cannot be representations of meanings of stimuli, either. They are observable manifestations from the material substrate of the meanings that are induced by stimuli, or that emerge from self-induced instabilities in the sensory and limbic systems. Their trajectory constitutes the evolution of a brain in its growth of experience [Piaget, 1930]. Similarly, a semantic device must be given opportunity to practice, experience, and grow in abilities to communicate.

The mechanism by which the formation of a wave packet is triggered is of particular interest. When an animal or human receives sensory information, it is carried not by any small number of axons from receptors but by a massive barrage of action potentials. A glimpse of a face, for example, includes all of the detectors for motions, contours, colors, and binocular disparities of the face, and also whatever background against which the face is glimpsed, such as a crowd, a factory, or a battlefield. The process involves two dozen or more specialized areas of cortex that process the sensory information, with multiple feedback pathways among them. Despite this enormous complexity, recognition occurs within half a second. The mechanism suggested by EEG analysis is that an entire sensory cortex is destabilized by input that is gated by a rapid eye movement (a microsaccade), and it jumps from one state to another. The transition is completed within 3-7 msec of onset [Freeman, 2003b]. It is followed within 25-35 msec by the formation of a spatial pattern of amplitude modulation [AM, Figure 2] of a chaotic carrier wave that persists for 80-100 msec. The AM pattern is accompanied by a spatial pattern of phase modulation [PM, Figure 2] that is radially symmetric with a fixed phase velocity in all directions. The PM pattern is measured by fitting to it a cone in the 2 surface dimensions of the cortex.

Figure 2 near here
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These two features, the AM and PM patterns, serve to characterize the spatial and temporal

location, size, duration and content of the wave packet that is triggered by sensory input. The AM pattern manifests the meaning of the stimulus, not the stimulus in itself, because the AM pattern changes when the context or significance of the stimulus is changed [Freeman, 1999, 2000a]. In contrast, the location and sign of the apex (maximal lead or lag) of the PM cone are random variables that do not reflect the properties of the stimulus that evoked it or its meaning for the subject [Figure 3]. The randomness of the sign implies that the apex cannot signify a pacemaker for the oscillation, which in any case is aperiodic. The proposed explanation is that the phase gradient manifests the formation of a wave packet by a 1st order phase transition [Freeman & Rogers, 2002], for which the location of the apex reveals the site of nucleation, and the velocity conforms to the finite rate of spread of the state change in a distributed medium, in the case of cortex by the conduction velocities of axons running parallel to the pial surface [Freeman, 2003b]. The phase gradient shows that the populations of neurons in the wave packet are not oscillating in phase at zero lag, but that they do so with leads or lags that increase with distance from the apex. This feature provides a soft boundary condition for the wave packet, which is determined by the half-power diameter. The mode and 95% inclusion diameters are shown by circles in Figure 4, which are superimposed on a diagram of the rabbit forebrain as seen from above. Wave packets having these properties were found in all of the sensory cortices examined, as shown by the rectangles indicating the size and locations of 8x8 electrode arrays used to detect the AM and PM patterns in the cortices.

Figures 3, 4 near here
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The massive size of the areas of cooperation leading to formation of wave packets provides an explanation for the speed with which pattern recognition takes place. The immense cloud of action potentials that is driven by sensory input from a stimulus undergoes a 1st order phase transition that is equivalent to formation of a rain drop from a cloud of

water molecules. In the process of the formation of a condensation disk, a spatial pattern of output is selected as the phase transition places the sensory cortex into the basin of an attractor that has been selected by the stimulus. The process repeats at frame rates between 2 and 7 Hz, as shown by the covariance of the successive phase cones with the low frequency oscillations in the theta range of the EEG [Figure 5].

 Figure 5 near here
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4. The neural basis for intentional action

The making of a representation is an intentional action. All intentional actions begin with the construction of patterns of neural activity in the limbic system, which have been shown by use of lesions and by comparative neuroanatomy and behavior to be a product of the limbic system [Herrick, 1948; Freeman, 1995]. In mammals all sensory input is delivered to the entorhinal cortex, which is the main source of input to the hippocampus, and the main target of hippocampal output [Figure 6]. Goal-directed action must take place with orientation and location in time and space. The requisite organ for these operations is the hippocampus with its 'short term memory' and 'cognitive map'.

 Figure 6 near here
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For example, hunger is an emergent pattern of neuroactivity that expresses the requirements of brains and bodies for metabolic fuel and building material. It induces a phase transition in the neural populations of the forebrain under the influence of sensory stimuli from the gut and the brain's own chemoreceptors for its chemical state. It is also shaped by neurohormones from nuclei in the brain stem. The emergent pattern impacts the brain stem and spinal cord, leading to stereotypic searching movements that are adapted to the immediately surrounding world. Feedback from the muscles and joints to the somatosensory cortex provides confirmation that the intended actions are

taking place. The impact of the movements of the body on sensory input is conveyed to the visual, auditory and olfactory systems. All of these perceptual constructs, that are triggered by sensory stimuli and are dependent on prior learning, are transmitted to the limbic system, specifically to the entorhinal cortex, where they are combined. When, for example, an animal detects an odor of food, it must hold the immediate memory of the concentration, move, take another sniff, and compare the two concentrations in order to decide which way to move next. The difference in strength has no meaning, unless the animal has a record of where it was when it sensed the first concentration, which way it moved, when the second sample was taken, and where, a basis for determining distance and direction in its environment from itself to its goal. These basic operations of intentional behavior are properties of the limbic system. The same requirements hold for all distance receptors, so it is understandable that evolution has provided multimodal sensory convergence in order to perform space-time integration on the multisensory percept, a Gestalt, not on its components prior to their assembly. These operations are already commonplace in robotics [Tani, 1996; Clerk, 1997]. What is not so well done is their integration into goal states, as described by Ashby [1952] and Walter [1953].

In the description thus far the flow of neural activity is rightward in Figure 6 from sensory systems to motor systems, then through proprioceptive and exteroceptive loops outside the brain back to the sensory systems. Within the brain there is a leftward flow of activity constituting reafference (the leftward arrows from "motor" to "sensory" systems). When a motor act is initiated by the limbic system when it issues a command as an activity pattern descending into the brain stem and spinal cord, copies of this activity pattern are sent along these internal pathways to all of the sensory systems by the entorhinal cortex. These 'efference copies' [Sperry, 1950] prepare the sensory processors for the impact on the sensory systems of the movements of the eyes, head, ears, and body and, most importantly, the efference copies sensitize the sensory cortices selectively by shaping their attractor landscapes to respond only to stimuli

that are appropriate for the goal toward which the action has been directed. The efference copy has also been denoted as a 'sense of effort' [Helmholtz, 1879], a 'reafferent' signal [von Holst & Mittelstaedt, 1950], and as a 'preafferent' signal [Kay & Freeman, 1998]. They are the essence of selective attention. These concepts are familiar in feedback control. They can and should be generalized into the context of the genesis and control of intentional behavior.

5. Linear versus circular causality in self-organizing systems

The conventional view of sensory cortical function holds that stimuli activate receptors, which transmit to sensory cortex through a linear causal chain, leading eventually to a motor response to the initiating stimulus. Modeling with nonlinear dynamics shows that the stimulus is typically not the initiating event. Rather it is the search for the stimulus that arises in conjunction with the evolving goal in the limbic system, which emerges in a recurrent manner from prior search and its results. This is circular causality at the level of intentional behavior [Merleau-Ponty, 1942].

Much lower in the hierarchy of brain organization is another instance of circular causality. This is the creation of the wave packet in the primary sensory cortex, which consists of the destabilization of a pre-existing mesoscopic state by the introduction of microscopic sensory input. In this case the transition from a prior basin of attraction to a new one, which has been facilitated by limbic modulation, is guided by the sensory input that activates a learned nerve cell assembly comprising a small subset of cortical neurons. The input from the receptors includes both the expected stimulus and the massive receptor discharge evoked by everything that is in the background. The total receptor input forces the instability and triggers the phase transition, and the nerve cell assembly that is activated by the expected stimulus selects the basin of attraction that captures the cortical system. Then the entire domain of the primary sensory cortex transits to the pattern that emerges as the system converges to the attractor in the basin, which in the words of

Haken [1983] "enslaves" the whole set of cortical neurons by acting as an "order parameter". This new active state has been characterized by Ilya Prigogine [1980] as a "dissipative structure", that constitutes, in his words, the "emergence of order out of chaos".

The similarity of the properties of neural activity in the various parts of the limbic system to those in the primary sensory cortices [Freeman, 1999] indicates that populations of neurons there also maintain global attractors, which are accessed by nonlinear phase transitions, and which are responsible for the genesis of goal states, their motor patterns controlling goal-directed actions, and the refference patterns that prepare the sensory cortices for the consequences of those actions.

The construction of a system or device that can simulate the creative dynamics of the brain by mapping from brain activity to behavior [Wright et al., this volume; Basar, this volume; Jerza, this volume] has been pursued in many laboratories with diverse foundations. My own approach has been based primarily on the dynamics and architecture of the olfactory system, both in software [Freeman, 1992; Freeman et al., 1997; Kozma & Freeman, 2001] and in hardware [Eisenberg, Freeman & Burke, 1989; Principe et al., 2001]. The basic unit of the construction is a neuron population called a KO set, that is roughly equivalent to an average neuron [Freeman, 1975]. Its time-dependent dynamics is governed by a linear 2nd order ordinary differential equation that is evaluated by fitting its solution as a sum of two exponentials to derive the coefficients for the rate of rise of the impulse response and the passive decay rate of the membranes. Its input is provided by lines that terminate in simulated synapses represented by gain coefficients that are subject to change by learning, and its output is bounded by a static nonlinear gain curve, which is the derivative of the sigmoid curve [Freeman, 2000a] relating dendritic current amplitude to pulse density output of the population.

An interactive population of excitatory neurons is called a KI_e set, and is made by

feedback connections between two excitatory KO_e sets in positive excitatory feedback. Similarly a KI_i set is made by feedback connections between two KO_i sets in positive feedback. KI sets have zero and non-zero point attractors and can generate sustained excitatory and inhibitory biases. A KII set is made by negative feedback connections between a KI_e set and a KI_i set. It is capable of limit cycle behavior. The interconnection and interaction of three KII sets with distributed feedback delays forms a $KIII$ set [Figure 7], that is capable of aperiodic, nonconvergent, sustained output [Figure 8] governed by a chaotic attractor, in addition to outputs governed by point and limit cycle attractors. An example of the temporal spectrum and amplitude histogram is shown in Figure 9, superimposed on the relevant portion of the nonlinear gain curve, which is the derivative of the sigmoid function governing pulse density in relation to dendritic current density [Freeman 2000a]. Figure 10 compares a spatial pattern of EEG from a sensory cortex experimentally derived from an 8x8 array of recording electrodes with a simulation using a $KIII$ set embodying an 8x8 array of coupled KII sets in the OB layer of a $KIII$ set [Freeman, 1992; Freeman et al., 1997; Kozma & Freeman, 2001].

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Figures 7-10 near here

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6. A hypothesis on the relations of meanings and representations

The hypothesis is proposed here that representations are formed by the motor systems through the forward, outward flow of neural activity. The motor commands are formed at the mesoscopic level by the interactions of neurons and neuronal populations, and they place the motor systems of the brain stem and spinal cord into appropriate basins of attraction. The representations emerge as spatiotemporal patterns of activity in the effectors of the body (the musculoskeletal apparatus, the autonomic nervous system, and the neuroendocrine nuclei), which respond to the volleys of action potentials from motor neurons at the microscopic level, i.e. single motor units

activated in concert. The movements of the body, supported by the autonomic and neuroendocrine back-ups, change the sensory inflow in a goal-directed manner. The actions elicit sensory feedback not only to the individual in action. The representations, as intended, activate patterns of receptor discharge in other beings, that place their sensory cortices into the expected basins of attraction. The receivers likewise create patterns of meaning, that lead to up-dates in their limbic systems, re-formation of motor commands, and behaviors that re-transmit representations to the original actor. Thereby, the circular causal chain is maintained between the two communicators.

The internal back flow of neural activity serves as an order parameter to modulate and shape the neural activity patterns of the sensory cortices, which transmit the states of their neural populations before and after the expected inputs have occurred, and also if they do not occur as expected, or at all. It comprises not only the exteroceptive input but the proprioceptive feedback as well. I infer that the organisms constructing and transmitting representations cannot know their meanings until the sensory consequences have been delivered to their own limbic systems. More generally, a poet, painter, or scientist cannot know the meaning of his or her creation until after the act has been registered as an act of the self, nor until the listeners and viewers have responded with reciprocal representations of their own, each with meaning unique to the recipients.

Why do brains work this way? Animals and humans survive and flourish in an infinitely complex world despite having finite brains. Their mode of coping is to construct hypotheses in the form of neural activity patterns and test them by movements into the environment. All that they can know is the hypotheses they have constructed, tested, and either accepted or rejected [Piaget, 1930; Merleau-Ponty, 1942]. The same limitation is currently encountered in the failure of machines to function in environments that are not circumscribed and drastically reduced in complexity from the real world. Truly flexible and adaptive intelligence operating in realistic environments cannot flourish without

meaning.

This assembly of interacting wave packets may be regarded as a mechanism supporting consciousness, which, in the neurodynamic view, is a spatiotemporal pattern of activity that occupies the entire forebrain. It is an internal state variable that has a trajectory composed of a sequence of transitory states that correspond to awareness [Hardcastle 1995]. Its regulatory role transcends that of the operator in a thermostat, although they share the properties that instantiate the difference between the state of the environment and expectation, such as a sensed temperature and a set point, and that initiates corrective action respectively by intentional action or by turning a heater on or off. The difference is that the simple machine state variable has little history and no capacities for learning or determining its own set point, but the principle is the same: the internal state is a form of energy, an operator, a predictor of the future, and a carrier of information that is available to the system as a whole. The feedback device is a prototype, an evolutionary precursor, not to be confused with awareness, any more than tropism in plants and bacteria is to be confused with intentionality. In animals and humans, the operations and informational contents of this global state variable constitute the experience of causation.

7. Summary

Semantics deals with the relation between meanings and representations, widely known as intention, 'aboutness', or the symbol grounding problem. Brains obtain information about their environments through the consequences of the intentional actions that they execute using their bodies. Studies of the spatiotemporal patterns of electroencephalographic (EEG) potentials that are induced by conditioned stimuli in the primary sensory and limbic cortices of trained animals have shown that the information thus obtained is used to construct meanings and is then discarded. Computers use representations for information processing and symbol manipulation, but brains have no internal representations. They deploy dynamic neural operators in the form of

neural activity patterns that construct and implement meaning but not information. Observers can describe these patterns as information, but that does not imply that the brain does so, or needs to. Brains construct external representations of their meanings in the form of shaped objects or movements as their mechanism for expressing their internal states. Examples are facial expressions and gestures in animals and words in humans. Those material constructs are made with the intent to elicit meaning in other brains, but they have no meanings in themselves and do not carry meanings as if they were buckets or placards. Meanings can only exist in brains, because each meaning expresses the entire history and experience of an individual. It is an activity pattern that occupies the entire available brain, constituting a location in the dynamic state space of a brain. EEG data indicate that neural patterns of meanings in each brain are based in mesoscopic wave packets that follow trajectories in discrete steps. Each step is demarcated by a 1st order phase transition that enables formation of spatiotemporal patterns of chaotic oscillations in the gamma range. Amplitude modulation of the carrier wave is the mode of expressing meanings. These wave packets do not represent external objects; they embody and implement the meanings for each individual of his or her interactions with the environment.

Engineers who propose to make semantic machines are faced with the task of defining meaning, which at present exists only in brains, and then with the task of learning how to design machines that can make or cause meaning in themselves [Tani, 1996; Clark, 1997]. The requirements on network models to simulate the chaotic dynamics of brains include global though sparse connectivity, continuous time dynamics, and distributed spatial functions in two-dimensional arrays of nonlinear integrators. Digital hardware may suffice to emulate the biological functions of sensory cortex in brains by use of nonlinear difference equations as in KIII sets [Chang & Freeman, 1996; Shimoide & Freeman, 1995; Freeman et al., 1996], provided that the problems can be solved of attractor crowding and numerical instabilities that inhere in digital representations of chaotic dynamics

[Freeman et al., 1997; Kozma & Freeman, 2001]. Digital simulation is a useful step toward analog simulation in VLSI [Principe et al., 2001], by means of which to attain the computational speed that will be required for real-time operation of the device. In this way, the following step toward machine intelligence can be to use a KIII model of a sensory cortex as an interface between the unconstrained real world, which is infinitely complex, and the finite state automaton that will rely on a dedicated digital computing system as the main support for its artificial

intelligence. That is, a model from brain dynamics can provide the eyes and ears for a conventional computer, that can enable the device to interface effectively with the infinitely complex environment that it will share with its designers, and about which it will be able to communicate its views.

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Figures

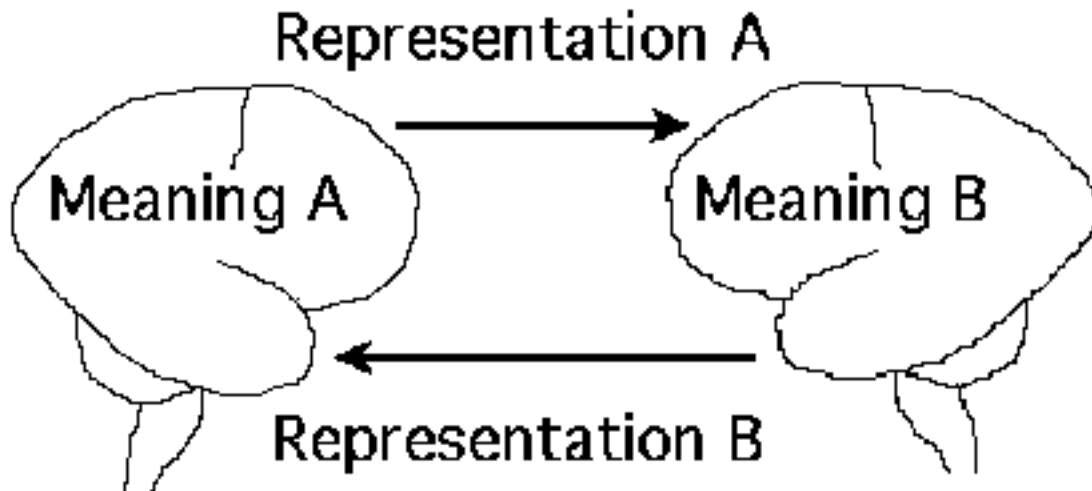


Figure 1 The schematic shows the roles of representations, $R(a)$ and $R(b)$, in the communication of meanings, $M(a)$ and $M(b)$, between individuals by the exchange of information carried by representations. A method is proposed to replace one of the communicants with a machine.

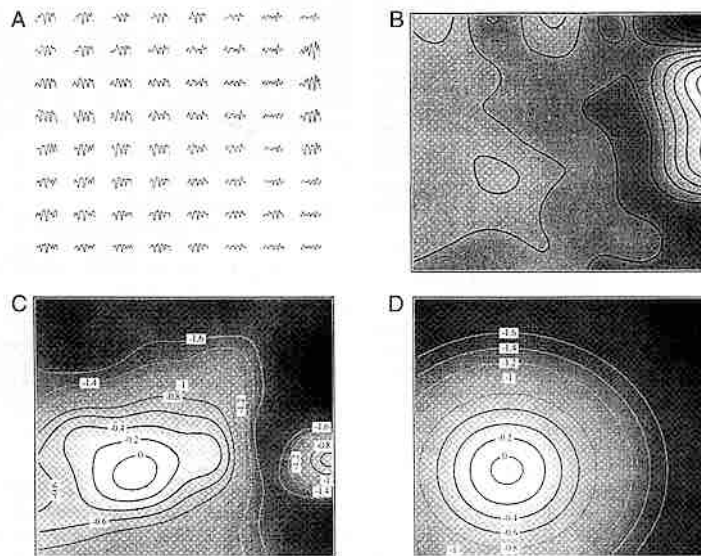


Figure 2. **A.** EEG traces from an 8x8 electrode array (6x6 mm) in a representative 64 msec segment from visual cortex after band pass filtering in the gamma range (20-80 Hz). **B.** Spatial AM pattern from RMS amplitudes. **C.** Spatial PM pattern at the peak frequency. **D.** A cone was fitted to the phase values. From Barrie et al. [1996].



Figure 3. Phase distributions were measured with respect to the phase of the spatial ensemble average at the surface of the olfactory bulb and fitted with a cone in spherical coordinates. The sketch is a projection of the outline of the bulb as it would appear on looking through the left bulb onto the array on the lateral surface of the bulb. A representative set of isophase contours is at intervals of 0.25 radians/mm. The locations of the apices of the cones on the surface of the sphere (2.5 mm in radius) are plotted from the center of the array to the antipode. The square outlines the electrode array. The standard error of location of points was twice the radius of the dots. From Freeman & Baird [1987].

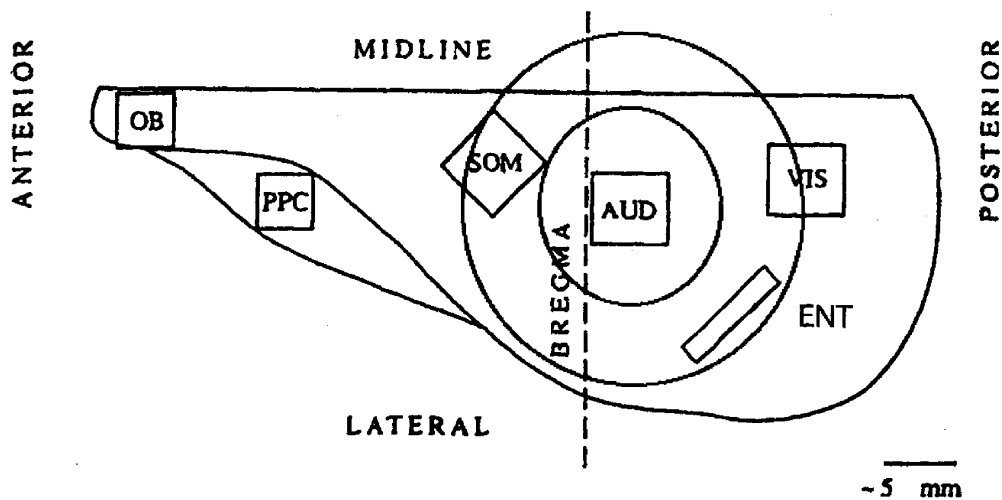


Figure 4. The outline shows the left cerebral hemisphere of the rabbit as seen from above. The rectangles show the approximate locations of the 8x8 arrays placed on the olfactory bulb (OB), prepyriform cortex (PPC), somatomotor cortex (SOM), auditory cortex (AUD), and visual cortex (VIS), and a 2x8 array on the entorhinal cortex (ENT). The inner circle shows the modal diameter of phase cones. The outer circle shows the diameter including 95% of cases. The vertical line is the zero stereotaxic reference. Adapted from Barrie et al. [1996].

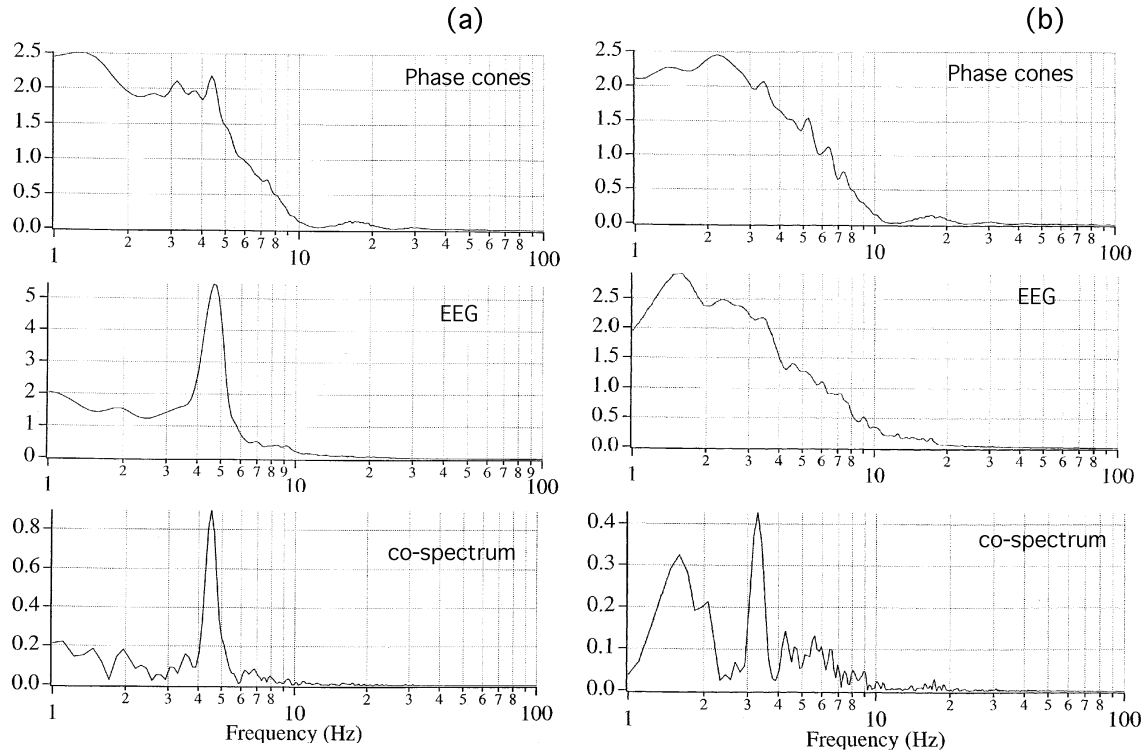


Figure 5. The amplitude (square root of power) spectra and coherence spectrum of the autocovariances and crosscovariance of the phase cones and EEGs were plotted as a function of log frequency. The cones were derived from EEGs temporally and spatially filtered to extract the gamma activity. The spectra of EEGs without gamma band filtering (only analog, 1-100 Hz) revealed their typical "1/f²" form. **a.** This example from the auditory cortex shows prominent theta peaks in the EEG, phase cones and coherence spectrum. **b.** The example from visual cortex has little theta in EEG or phase cones but a clear peak in the coherence spectrum.

DYNAMIC ARCHITECTURE OF THE LIMBIC SYSTEM

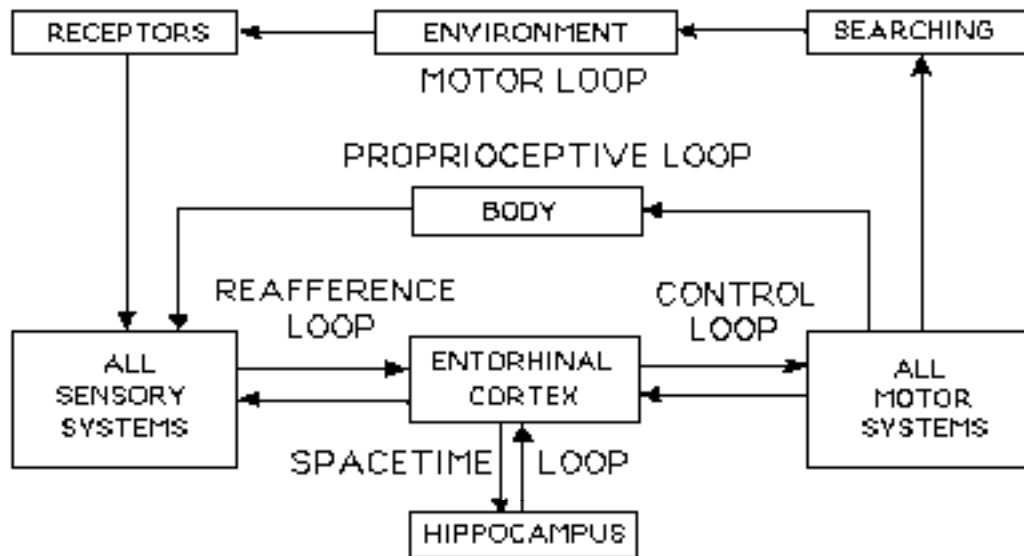


Figure 6. A schematic diagram summarizes the main elements in the dynamics of intentional behavior to aid in the design of a device that is capable of intentional action, including semantic communication. From Freeman [2000b].

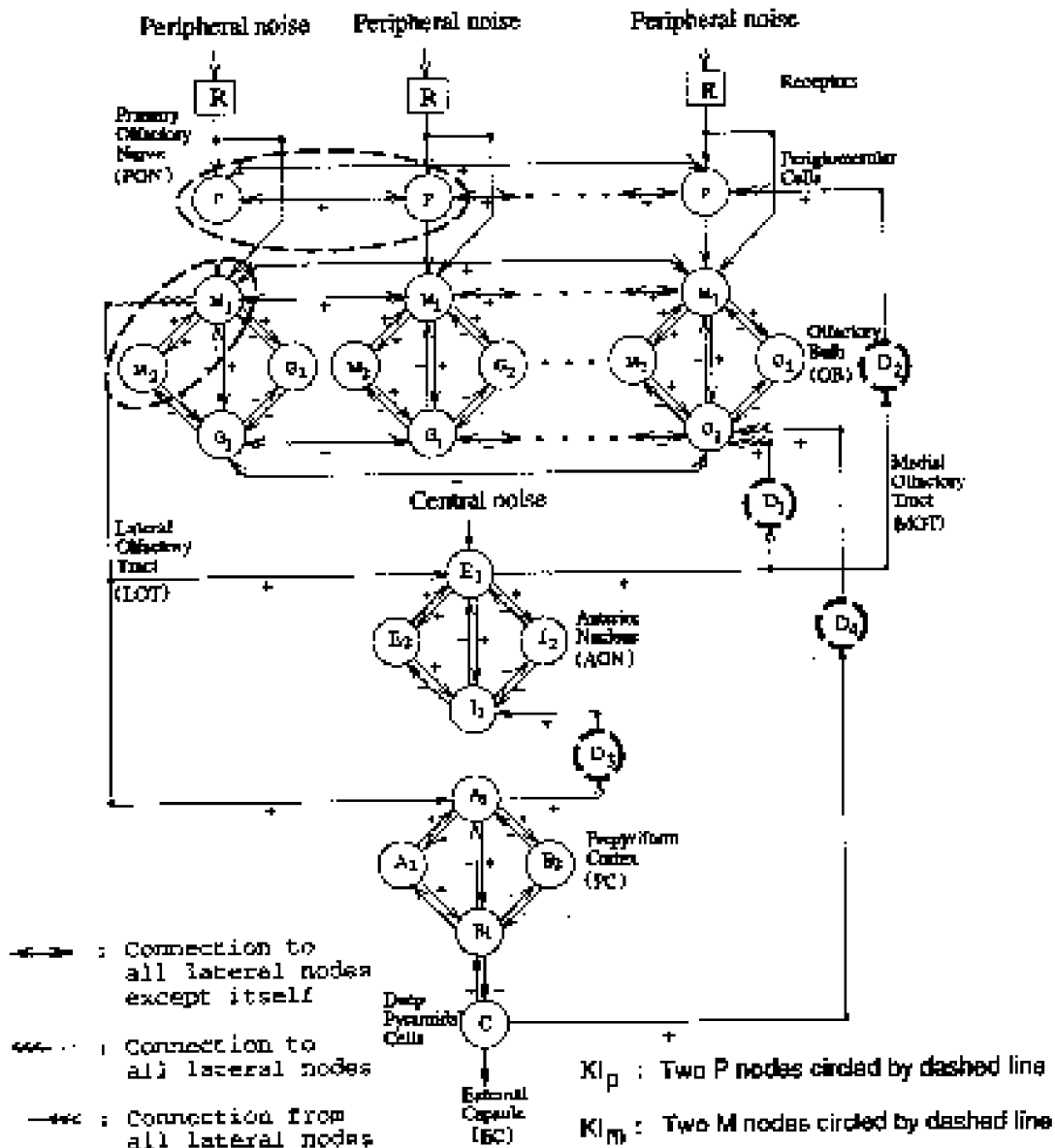


Figure 7. The flow diagram shows the KIII model of the olfactory system. The main parts are the layer of receptor neurons (R), the olfactory bulb (OB), anterior olfactory nucleus (AON) and prepyriform cortex (PC), containing excitatory cells (M = mitral, E and A), inhibitory interneurons (G, I and B), excitatory interneurons (PG), and deep pyramidal cells (C). The cells in the OB, AON, and PC form feedback loops that sustain limit cycle oscillations at incommensurate frequencies. The long pathways that interconnect the oscillators lead to emergence of nonconvergent, aperiodic oscillations in the three structures with $1/f^2$ spectra in log-log coordinates. From Freeman et al. [1997].

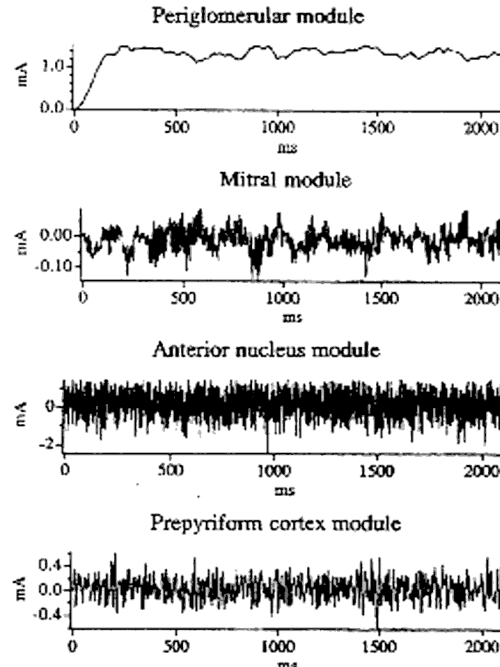


Figure 8. The simulated EEGs of the PG, OB, AON and PC are shown in the background control state without deliberate stimulation. From Freeman et al. [1997].

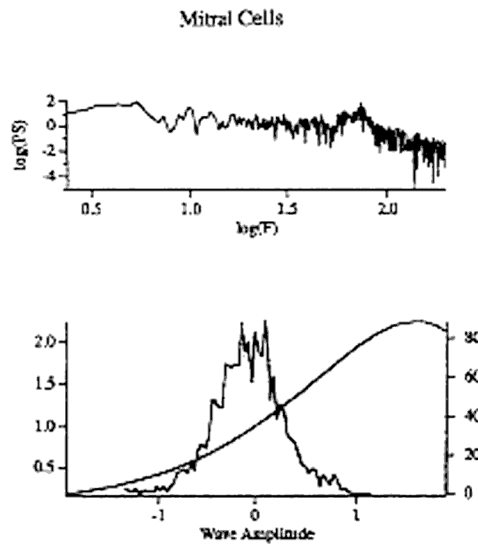


Figure 9. An example is shown of the spectrum of the simulated EEG (upper frame) and of the amplitude histogram, typically nearly Gaussian, superimposed on the nonlinear gain curve that governs the input-output function of neural populations. The upward slope of the gain curve with increasing excitation of the neurons reflects the intrinsic property of neurons, that their excitability increases exponentially as they are brought closer to threshold by excitation. This is the property that underlies destabilization of a neuron population by excitatory input. From Freeman et al. [1997].

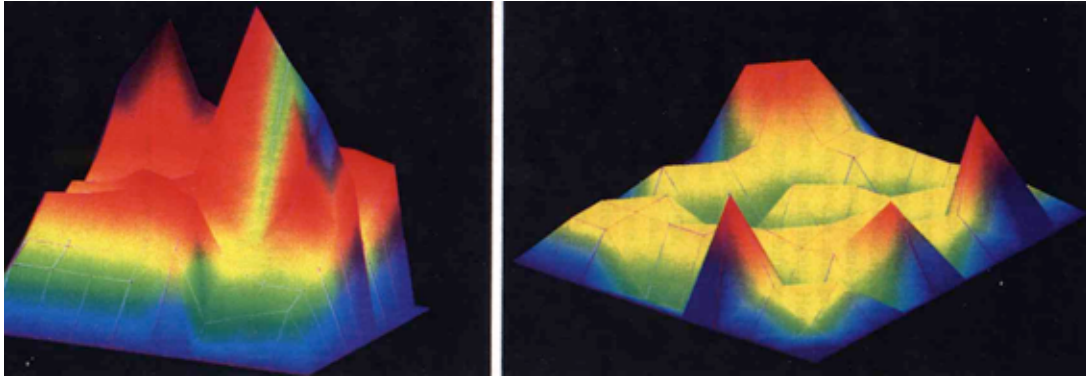


Figure 10. Left Frame. An example is shown of a spatial pattern of the amplitude modulation (AM) of the aperiodic carrier wave in a wave packet observed at the surface of the olfactory bulb (OB) of a rabbit. **Right Frame:** An example is shown of an AM pattern that was simulated with a KIII model. From Freeman [1992].