Proceedings of Symposia in Applied Mathematics
Volume 52, 1997

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What is Mind that the Brain May Order It?

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Please remember that we are not now concerned with the physics and chemistry, the anatomy and physiology of man. They are my daily business.

Warren S. McCulloch 1965, in Chapter 1: *What is a Number that Man May Know It, and a Man that He May Know a Number?* (p. 7)

Contents

1. Introduction

Over the past 25 years there has been a convergence of interest on the problem of how conscious experience is generated. The convergence originates in mathematics, physics, brain science, cognitive psychology and philosophy (see King & Pribram 1995). Physicists especially have fertilized the endeavor with original contributions that attempt to bridge the gap between explanations of mind and of matter. However, most of their contributions are innocent of the work accomplished in systems neuroscience and in experimental psychology. And the obverse is also true: very few brain or behavioral scientists are interested in and conversant with the sweeping changes in thought that have characterized twentieth century mathematics and physics. Thus, on the occasion of the Centenary of the Birth of Norbert Wiener, the time is ripe for an appraisal of the paths of convergence and to acquaint a larger audience with the exciting vistas that are opening before us.

2. The Brain and The Computer

Neurons are ordinarily conceived to be the building blocks, the units of organization, of the brain. For the benefit of those not recently versed in the conceptions of the subject, let me first review this standard neuron based conception of the composition of the nervous system. However, as will be described in Section 2 of this essay, this emphasis on the neuron must be supplemented by additional configurations which operate to some considerable extent as processing "units" independent of the neuron.

Anatomically, neurons are composed of a cell body to which are attached a set of branching input fibers called *dendrites* (rootlets). Extending from one location of the cell body of the neuron (its *axon hillock*) is a chemically different sort of nerve fiber, often longer than the others, called the *axon*. At its terminus the axon splits into smaller branches called *nerve-terminals* or *teledendrons*. There is a minute gap called a *synapse* between the far terminus of an axon and the dendrites or cell body of the adjacent axon on which it impinges.

Energy inputs to dendrites are exceedingly small and must, therefore, "summate" in some way to influence (modulate) the nerve impulses that are generated by the chemical processes operating at the axon hillock. The resulting modulated series of nerve impulses propagates down the length of the axon until it reaches the teledendrons of its far terminus. When the nerve impulses reach the teledendrons, they produce one or other chemical, called a *neurotransmitter*, that diffuses across the synapse. This diffusion creates an electro-chemical potential difference in the dendrites of the post synaptic neuron. This potential difference in the post synaptic neuron can be *excitatory*, called *depolarizing*, or *inhibitory*, called *hyperpolarizing*.[1] There are myrials of such synapses in the brain. I shall refer to the activity initiated at synapses that produces depolarization and hyperpolarization in the dendrites as occurring in the brain's *connection web*.

The majority of neural processing theories since the seminal contribution of McCulloch and Pitts (1943) have taken the axonal discharge of the neuron, the nerve impulse, as the currency of neural computation. The knowledge that the neuron has only two states "firing" or "quiet" suggested comparison with the

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1 **hyperpolarize** The act of making the internal surface of a neuronal membrane more negative with respect to the outside, usually by the exit from the cell of positively charged ions (potassium).

depolarize Act of making the internal surface of a neuronal membrane more positive with respect to the external surface, usually by the entry into the cell of positively charged ions (sodium and calcium).

electronic computer. In their gross structures the brain and the digital computer were thus thought to have marked similarities. As Wiener noted in 1948:

> . . . the ultra-rapid computing machine, depending as it does on consecutive switching devices, must represent almost an ideal model of the problems arising in the nervous system. The all-or-none character of the discharge of the neurons is precisely analogous to the single choice made in determining a digit on the binary scale . . . The synapse is nothing but a mechanism for determining whether a certain combination of outputs from other selected elements will or will not act as an adequate stimulus for the discharge of the next element, and must have its precise analog in the computing machine. The problem of interpreting the nature and varieties of memory in the animal has its parallel in the problem of constructing artificial memories for the machine. Wiener [61c, p. 14]

However, from a fine structural standpoint the brain is considerably more complex than the digital computer, and by the 1960's it was realized by some of us that the McCulloch-Pitts theory was inadequate.[2] The branching structure of dendrites (the so-called *dendritic tree*) plays a far more important and diverse role than was initially surmised, as we shall see. Furthermore, analogue computation also plays a significant role in neural computing.

3. The New Neurology

My own approach in the mid 1950's differed from that of McCulloch-Pitts and the early Wiener, by focusing on the relationship of neurophysiology and mind, and taking *computer programming* rather than computer hardware as its metaphor.

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[2] Wiener too realized the erroneousness of his earlier estimation, witness his words in 1964 in a posthumously published paper.

> It is now clear that this all-or-none character is the result of the long duration in time and the long continuance in space of nervous conduction under essentially constant conditions. It is not to be expected then in a short fiber in which the remaking of the initial impulse has not had headway enough to assume its final shape or in which there are non-homogeneities such as incoming or outcoming branches as in the teledendron or the dendrites. Therefore the pattern of all-or-none activity, where highly suitable for the conduction of nervous activity in the white matter, is by no means so suitable for the study of the same sort of activity in the gray matter. As a matter of fact I believe there is positive evidence that the all-or-none hypothesis applied to the gray matter leads to false conclusions. Wiener [65b, p. 401]

At some point in programming, there is a direct correspondence between the programming language and the operations of the hardware being addressed. In ordinary serial processing, machine language embodies this correspondence in an easily recognizable way. Higher order languages encode in more subtle ways the information necessary to make the hardware run in more abstract and therefore general useful languages. When a word processing program allows this essay to be written in English, there is no longer any similarity between the user's language and the binary of the computer hardware. This, therefore, initially appears as an erroneously conceived irreconcilable dualism between mental language and material hardware operations. When, however, all the transformations, the recoding operations that lead from binary through hexadecimal codings, assemblers, operating systems and the like are available, the connection between the binary system and English becomes transparent.

Transposed from metaphor to the actual mind-brain connection, the operations of the connection web seem far removed in their organization, from the organization of our thoughts and of the psychological processes that we describe in observation sentences such as "I see a red apple." But the separation between these organizations is of the same range as that between computer programmed word processing and binary processing.

What is different in the mind-brain connection from that which characterizes the program-computer relationship is its intimate parallel processing of self-organizing structures at every level. For instance, the optic nerve, which transmits visual information, has more than half-a-million parallel fibers. High level psychological processes such as those involved in cognition are therefore the result of cascades of parallel operations, involving two-way feedbacks, rather than, as in computers, the result of fairly fixed top-down programming operations.

These differences between classical computer and neural programming have led to new developments in parallel processing programming architectures called *neural networks*. Successful computations in these networks depend on highly -- often fault tolerant -- interconnected elements. The more diverse the computation, the more connections are needed.

However, classically, neuroscientists have shown that neuronal pathways are sometimes relatively sparse, and always in a specifically configured fashion. Lashley (1942) was puzzled by this anatomical fact which is ubiquitous but seems to be incompatible with the fact that psychological processes depend on patterns that can be transposed from one location in the body or its environment to another.[3]

The problem becomes resolved when the computational framework of the neurosciences is broadened beyond nerve-impulse-transmission, to include the microprocessing that takes place within the brain's connection web. The myriad of synapses provide the possibility for *processing* as opposed to the mere *transmission* of signals. The term *neurotransmitters* applied to chemicals acting at synapses is, therefore, somewhat misleading. Terms such as *neuroregulator* and *neuromodulator* convey more of the meaning of what actually transpires at synapses. When nerve impulses arrive at synapses, potential differences are enhanced creating hyper- and depolarizations. These are never solitary but constitute arrival patterns. The patterns are constituted of the periodically fluctuating hyper- and depolarizations which are insufficiently large to immediately incite nerve impulse discharge. The delay entailed in the passive diffusion of these patterns affords opportunity for computation. The synapses occur in layers in the brain's connection web, and there are axons bridging the layers of the cortex. Thus, the microprocessing mentioned in the previous paragraph provides the unconstrained high connectivity needed in computational processes.

A major breakthrough toward understanding the minute architecture of the connection web was achieved by Kuffler (1953). He moved a spot of light in front of a paralyzed eye and recorded the locations of the spot that produced a response in the axon of a retinal ganglion cell. The direction of response, inhibitory (-) or excitatory (+), at each location indicated whether the input branches (dendrites) at that location were hyperpolarizing or depolarizing. The locations revealed the topology, the extent and configuration of the responding dendritic arborization of that axon's parent neuron. The resulting diagrams of hyper- and depolarization thus revealed the *receptive fields*,[4] which activate the

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3 An example of the transposability of patterns is the reasonable fidelity of writing with one's left hand or left big toe in the sand -- or even one's teeth -- when one has never previously engaged the neuromuscular apparatus in this fashion. Even writing on the vertical surface of a blackboard engages the neuromuscular system in a different fashion from when writing is accomplished on a horizontal surface.

4 *Receptive Field* is defined as the area in sensory space, i.e. physical space outside the body, within which an adequate stimulus causes an excitatory response of the neuron from which recordings are being made. It is often surrounded by a sensory region, called the *nonclassical receptive* field, that

dendrites of that axon. The receptive fields of retinal ganglion cells are found to have a circular inhibitory or excitatory center surrounded by a penumbra of opposite sign.

Utilizing Kuffler's techniques of mapping, Hubel and Wiesel (1959) discovered that for cerebral cortex the circular organization of the receptive field become elongated displaying definite and various orientations. They showed that oriented lines of light stimuli rather than spot stimuli produced the best response recorded from the axons of these cortical neurons. They therefore concluded that these cortical neurons were *"line detectors."* In keeping with the tenets of geometry where lines are made up of points, planes of lines and solids of planes, Hubel and Wiesel suggested that line detectors were composed by convergence of inputs from neurons at earlier stages of visual processing (retinal and thalamic -- which acted as spot-detectors due to the circular center-surround organization of the receptive fields.) This geometric interpretation of neuronal processing led to a search for convergences of paths from "feature detectors"[5] such as those responding to lines, culminating in "pontifical" or "grandfather" cells that embodied the response to object-forms such as faces and hands. The search was in some instances rewarded in that single neurons might respond *best* to a particular object form such as a hand or face (Gross, 1973). However, response is never restricted to such object-forms. Such "best" responses can also occur in parallel networks made up of neuronal ensembles in which convergence is but one mode of organization.

For those using the geometric approach, spots and lines are seen as elementary features that become combined in ever more complex forms as higher levels of the neural mechanism are engaged. In the late 1960's, however, new evidence accrued (see DeValois and DeValois, 1988 for review) that called into question the view that figures were composed by convergence of features and indicated that harmonic analysis was a better representation of what occurred in the brain.

4. The Brain as Harmonic Analyzer

A century ago, Helmholtz proposed that sensory receptors are akin to a piano keyboard; that a spatially isomorphic relation is maintained between receptor and cortex as in the relation between keys and strings of a piano, but that each cortical

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can modulate the central response.

5 By a *feature detector* is meant that unit of a network which responds selectively *and uniquely* to a particular organization in its receptive field, such as an edge, line, circle or color.

"unit" responds (resonates) to a limited bandwidth of frequencies as do the strings attached to the piano's sounding board. From the operation of the total range of such units, magnificent sounds (in the case of the piano) and sights (by means of the visual system) are engendered. James Clark-Maxwell too made a statement that foreshadowed the promise that such a harmonic approach might provide understanding to the brain/mind relationship:

> It would not be devoid of interest, had we opportunity for it, to trace the analogy between these mathematical and mechanical methods of harmonic analysis[6] and the dynamical processes which go on when a compound ray of light is analyzed into its simple vibrations by a prism, when a particular overtone is selected from a complex tune by a resonator, and when the enormously complicated sound-wave of an orchestra, or even the discordant clamors of a crowd, are interpreted into intelligible music or language by the attentive listener, armed with the harp of three thousand strings, the resonance of which, as it hangs in the gateway of his ear, discriminates the multifold components of the waves of the aerial ocean. (J.C. Maxwell, "Harmonic Analysis", *Scientific Papers*, II, pp. 797-801)

Let us turn to the new evidence that accrued in the late 1960's which lent credence to this view of the brain. In my laboratory at Stanford University, we exposed the eye to moving dots on a computer screen and studied the different configurations of responses of the dendrites of cortical neurons, much as Kuffler had done on the retina. We found regions that contained not only a single oriented line, as had been reported by Hubel and Wiesel, but bands of excitatory (indicated by an increase in firing) and inhibitory (indicated by a decrease from baseline in the neuron's firing) areas. Other workers arrived at similar conclusions. In a critical report, Pollen, Lee, and Taylor (1971) interpreted their findings to indicate that the cortical neurons were behaving as Fourier analyzers rather than as line detectors. When harmonic analysis is taken as the approach, the "line detectors" are interpreted as "strings" tuned to a limited bandwidth of frequencies. The ensemble of strings act as resonators or active filters, as in musical instruments.

Indeed in the late 1960's, Campbell and Robson (1968) initially on the basis of psychophysical and subsequently on the basis of neurophysiological experiments, developed the thesis that vision operates harmonically much as does

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6 Maxwell was alluding to the harmonic analyzer designed by Lord Kelvin for spectral analysis of tidal waves.

audition, except that the visual system responds to *spatial* frequencies in the Fourier transform of the visual stimulus.[7]

There are four critical reasons for preferring the detection of frequencies to that of geometric features: (a) Each neuron in the visual cortex responds to several features of sensory input, and there is no evidence that the different features are uniquely represented by any single neuron, as would be required if it acted as a feature detector. For instance, changes in orientation, spatial frequency, luminance, direction and velocity of the stimulating input all can alter the output of the neuron as gauged by its axonal discharge. (b) The form of the activity of the connection web of such neurons, as gauged by their receptive field configuration, can be accounted for by considering them as spatially and temporally constrained frequency resonators. (c) These resonators provide a potentially richer panoply for the perception of texture and parallax than do feature detectors. (d) Perceptual research has clearly shown that lines (and therefore line detectors) composing contours are inadequate elements with which to account for the pattern recognition in vision. (See Pribram 1991, Lectures 2 and 3 for details.)

Harmonic analysis has also contributed to neuroscience by its explanation of our conscious experiencing of images and objects. For instance, in every-day life we become consciously aware of a three dimensional acoustic image in

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[7] Spatial frequency. For the simple harmonic disturbance in three-dimensions:

$$\psi(t,x) := a(x)e^{2\pi i\nu t}, \qquad x = (x_1, x_2, x_3) \in \mathrm{IR}^3$$

with space-dependent complex amplitude a, one takes the Fourier transform of this amplitude

$$\hat{a}(p) = \int_{\mathrm{IR}^3} e^{2\pi i(p_1x_1+p_2x_2+p_3x_3)} a(x)\,dx, \qquad p \in (\mathrm{IR}^3)^\wedge.$$

The vector $p \in (\mathrm{IR}^3)^\wedge$ is called a *spatial frequency*, and $(\mathrm{IR}^3)^\wedge$, the *spatial spectral domain*. Since

$$\begin{aligned}\psi(t,x) &= a(x)e^{2\pi i\nu t}\\ &= \int_{\mathrm{IR}^3} e^{2\pi i\{\nu t-(p_1x_1+p_2x_2+p_3x_3)\}}\,\hat{a}(p)\,dp,\end{aligned}$$

we see that p is the *wave vector* and $|p|$ the *wave number* of the harmonic component of ψ having the infinitesimal amplitude $\hat{a}(p)\,dp$.

stereophonic high fidelity reproduction of music. We know the sources of the sound to be the speakers, but we also know that by adjusting the phase relationships between acoustic waves generated by the speakers, we can move the sound away from the two sources, to in-between the speakers or in front of them. Our ears and acoustic nervous systems reconstruct the sound to be perceived in a location we know to be incapable of producing that sound.

What determines this construction of a sound image away from its physical source? Bekesey's ingenious experiments (1960, 1967) with artificial cochleas[8] hold the answer. By lining up five vibrators on one's forearm, Bekesey was able to produce the feeling of a single spot that could be moved up or down by changing the phase of vibrations between the vibrators. When a second artificial cochlea was placed on the opposite forearm, the feeling of a spot could be made to jump from one arm to the other. After a while the spot becomes "projected" out into the region between and in front of the arms away from the receptor surface of the skin much as sound is projected from two stereophonic speakers. However, using two arms is not a necessary condition for perceiving an image away from the receptor surface. When phase relations between stimulations to two fingers are adjusted, a spot can be projected outward from them. One feels the paper on which one is writing at the tip of one's pencil, not at the tip of the fingers holding it. Harmonic interactions among vibration are the necessary conditions for such perceptions. As indicated by the work of Fergus Campbell and his associates noted earlier, the projection of visual percepts is accomplished in like manner. And another example of the power of the harmonic view is provided by the extended series of experiments performed by James Gibson (1979), which utilized two dimensional displays on cathode ray tubes which are perceived as three dimensional figures. Gibson argued from his findings that three dimensional perception is "direct," i.e., immediate, and that all other forms of knowledge and the world are derived from this immediate reality. In a paper in which I take issue with Gibson (Pribram 1982) regarding what might be called the illusion of the"directness" of appearances, I describe the harmonic brain processes which are involved even when perceptions appear to be immediate.

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[8] Cochlea Organ of hearing in the *inner ear* consisting of a spiral structure containing three fluid-filled compartments. Fluid set into oscillation by sound waves causes movement of stereocilia (hairs) or *hair cells* which are the auditory neural transducers. Frequency response of hair cells is place coded on the cochlea, with high frequencies represented at the base of the spiral.

5. Holographic and Holonomic Process in the Brain

> Philosophically more important [than Wiener's power spectrum] is another mathematical creation of Wiener, the "coherency matrix," and this has a curious history. It was entirely ignored in optics until it was reinvented, almost simultaneously and independently, by Dennis Gabor in England in 1955, and by Hideya Gamo in Japan in 1956.[9] (Gabor 1981, p. 490)

In 1948 Dennis Gabor made the concept of coherence the basis of a mathematical theory aimed at improving the resolution of an image in electron microcopy. Instead of forming photometric images, which record intensities but destroy phase information, the photographic film ought to record the interference patterns of the light diffracted by the tissue to be examined. Only in the early 1960's did the advent of lasers provide the strong source of coherent light by which the process could be realized. These hardware realizations made it evident that images of the objects that had initially diffracted the light could readily be reconstructed.

Gabor named the record of interference pattern a ***hologram***. A holographic process is constructed of interference patterns resulting from the intersection of coherent wave fronts. One of its most interesting characteristics is that information from the object becomes distributed over the surface of the photographic film. The light diffracted from each point of the object gets spread over the entire surface of the film, and the superposition of the rippling wave forms originating from different points on the object leaves an intersecting pattern of interference nodes on the surface of the film. The spread is not haphazard, however: It embodies all phase relations. The ripples become distributed from the point of diffraction somewhat as ripples of waves formed when a pebble strikes the smooth surface of a pond of water. Throw a handful of pebbles into the pond, and the ripples produced by each pebble will crisscross with those produced by the other pebbles, setting up patterns of interfering wave fronts. The smooth mirror-like surface has become blurred, but the blur has hidden within it an unsuspected orderly pattern. A photograph of the pond at this moment would be a hologram. The photographic hologram is such a frozen record of the nodes of interference among wave fronts.

The fact that we are able to remember items of experience even when parts of our brain are damaged indicates that the same memory is stored over wide areas of the brain. Until recently, brain and behavioral scientists could not

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[9] Wiener's work on *optical coherence* (c. 1928) is discussed more fully in Professor Klauder's paper in these Proceedings.

conceive of *any* process that was consonant with the facts of brain anatomy and physiology and at the same time, spread sensory input sufficiently to account for the distributed memory store. But with the discovery of holography, it seemed immediately plausible that the distributed memory store of the brain might resemble this holographic record. I developed a precisely formulated theory based on known neuroanatomy and known neurophysiology that could account for the brain's distributed memory store in holographic terms (Pribram 1966; 1971; Pribram et al. 1975). In the decades since, many laboratories--including my own--have provided the evidence that has sharpened the theory and given it a more precise fit to the known facts (for a review see Pribram 1991, Lecture 2).

The theory states that sensory systems perform a series of operations that combine to yield the Fourier transformation of the input signal impinging on the retina (Gabor 1968; Pribram 1991, p. 73). Not only auditory processing but visual and somatic (skin, muscle and visceral) sensations are initially processed in the spectral domain. As noted, processing is accomplished in a connection web at the synapses among arborizations of neurons. Some neurons, now called *local circuit neurons*, have no axons and display no nerve impulses. Their function is primarily to influence the polarizations. They are most often found in the horizontal layers of neural tissue such as the retina and cortex in which interference patterns become constructed. This accounts for our remembering discrete items after brain damage. Sensory input must, in some form, probably as changes in the conformation of biomolecules at membrane surfaces, become encoded into distributed memory traces (see Pribram 1971, Chapter 2; Pribram 1996/In Press; and Jibu, Pribram and Yasue 1996/In Press). The biomolecules would serve as a neural "holoscape" in the same way as oxidized silver grains serve the photographic hologram.

Aside from these anatomical and physiological specifications, a solid body of evidence has accumulated that the auditory, somatosensory-motor, and visual systems of the brain do, in fact, process input from the senses in the spectral domain. (See Pribram 1991 and DeValois and DeValois 1988 for a review of the evidence.)

However, the patterns in the connection web are bounded by the anatomy of the neuronal branches. To deal with them, it is convenient to partition the time-frequency plane, and more generally the 5-dimensional space-time frequency hyperspace into Gabor's *logons*[10] (see Flanagan 1972 and Pribram 1991, pp. 28-

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[10] For the theory of the *logon*, a unit of *structural information* (not to be confused with the Shannon-Wiener information), the reader is referred to the Appendix of this paper.

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There is an aspect of harmonic analysis to which first Wiener and then, more thoroughly, Dennis Gabor contributed, viz. *the time-frequency restraint inherent in any signal*, an aspect which is germane to brain science. This is the restraint imposed by the inequality:

$$(1) \qquad \int_{-\infty}^{\infty} |tf(t)|^2\, dt \cdot \int_{-\infty}^{\infty} |\lambda \hat{f}(\lambda)|^2\, d\lambda \geq \frac{1}{4} \int_{-\infty}^{\infty} |f(t)|^2\, dt \cdot \int_{-\infty}^{\infty} |\hat{f}(\lambda)|^2\, d\lambda$$

that links a function f to its Fourier transform $\hat{f}$. In engineering circles, it is spoken of as the *time, band-width relation.*

During the 1970's these Gabor *elementary functions* f, for which equation (1) becomes an equality, (or *Gabor wavelets*, as they are now commonly called), were used to simulate the visual processing in the cortex, and it was found that the results matched closely the reality. As noted earlier, with the advent of frequency analysis in studies of figural processing[11] pioneered by Schade (1956), Kabrisky (1966), and Campbell and Robson (1968), the term "spatial frequency" known in optics became commonplace in the visual sciences. Applying to spectral processing a term coined by Heinrich Hertz (1884) to describe dynamical systems subject to constraints, I called the process described by Gabor as *holonomic* to emphasize that spectral processing in the nervous system is constrained by the boundary conditions imposed by the brain's anatomy.

To revert to Maxwell, the "harp of three thousand string" hangs not only in the gateway of the ear but is also present in the connection web that "resonates" at each stage of the brain's sensory pathways. Such resonances were historically modelled in terms of the mathematics that describe holography and then in terms of patch or constrained holography, that is, holonomy.

Finally, an important insight gained from the results of experiments involving brain information processing is that electrical stimulation of the posterior "association" cortex enhances processing in the image/object (space-time) domain, while such excitation of the frontal cortex enhances processing in the spectral domain (cf. Pribram 1991, Lecture 10). Thus, the constraints, "the boundaries" which are due to neural inhibition, are relaxed by electrical excitation of the frontal and related limbic formations of the brain. Processing under such circumstances becomes more unconstrained and holographic-like.

6. A Holonomic Universe. Leibniz

At least since the time of Newton and Leibniz, two rather different conceptual

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[11] i.e. the neural processing of geometrical forms.

schemes have dominated thinking. Both are concerned with the lawful relation between observed events. But the Newtonians express these relations in terms of the relations among material entities, whereas the Leibnizians explain them in terms of the constructive effect of oscillations (waves). The following statements place the Leibnitzian view as seen by Wiener into succinct apposition with the currently received view as held by most neuroscientists:

1. The received view: Brain, by organizing the input from the physical and social environment as obtained through the senses, constructs mental phenomena which are defined to include memory (Gr. *mnasthai*), attention (minding), intention (Gr. *menos* intent), thought (Sanskrit *manos*), as well as perceptions of images and objects and feelings such as love, fear and pain.
2. The Leibnitzian view: A pervasive organizing principle of the universe is a hierarchy of monads. All monads are informed, but with different degrees of clarity. Mental processes are able to discern the pattern of the cosmos by virtue of the brain's intunement (albeit imperfect) with the forms inherent in the universe.[12]

Almost all behavioral- and neuro-scientists would today subscribe to some form of statement one, while statement two reflects the belief of many theoretical physicists such as Einstein, Dirac and Schroedinger and others. Mathematicians and mathematical physicists have faced the dilemma more directly: How is it that the operations of their brains so often lead to discoveries of which the experimental physicist has no inkling, and which he is only able to verify later? Thus, as Dirac has written:

> It seems to be one of the fundamental features of nature that fundamental physical laws are described in terms of a mathematical theory of great beauty and power, needing quite a high standard of mathematics for one to understand it. You may wonder: why is nature constructed along these lines? One can only answer that our present knowledge seems to show that nature is so constructed. We simply have to accept it. One could perhaps describe the situation by saying that God is a mathematician of a very high order, and He used very advanced mathematics in constructing the universe. Our feeble

[12] Or, as C.S. Pierce (1960) so poetically stated it: "Every single truth of science is due to the affinity of the human soul to the soul of the universe imperfect as that affinity no doubt is" (4, 5.47)

> attempts at mathematics enable us to understand a bit of the universe, and as we proceed to develop higher and higher mathematics, we can hope to understand the universe better. Morris (1987), pp. 21, 22

Along with their fundamental atomistic researches in statistical mechanics and genetics, Norbert Wiener and J.B.S. Haldane made contributions that fit into the Leibnizian tradition and fit the theme developed during the second half of this century, which has been recounted in this paper.

I believe that those whose conceptualization operate primarily in the space-time domain find the emergentist view of mind most compatible, while those who are sensitive to the spectral domain (i.e. interference among wavelengths) are comfortable with the more interpenetrating Leibnizian view.

It is my contention that the advances in brain science, outlined in the previous sections, give considerable credence to the Leibnizian view, which is worth exploring farther, if only briefly, in so far as it bears on this issue.[13]

What is most important for us is Leibniz's *monadology*. Just as the mechanics of matter could be built *à la* Newton on the basis of the ideal concept of the *point mass*, so Leibniz held that the mechanics (or as he preferred to say, *dynamics*) of the spirit could be built on the ideal concept of a *point-mind or monad*. Each monad, like a tiny mirror, produces its own image of the universe. Point masses can vary: the mass can range over the set of positive real numbers. Likewise for monads. For although Leibniz offered no unit of perceptual range and clarity, he maintained that the range and clarity of the perception or vision of a monad can vary from the very short-ranged and very blurred, to the very long-ranged and sublimely sharp. (Today we know that Gabor wavelets have just these alternatives and can, therefore, serve as point-mind units—See Pribram 1993, epilogue.)

Unlike the Newtonian point mass, which, apart from its mobility in space, is eternally the same, the monad is not eternally fixed. By a principle of inner unfolding called *appetition*, the monad can develop its perceptivity. When this development reaches a point of clear self-consciousness, the monad is said to have attained *apperceptive consciousness*. But only a minority of monads are so conscious. As Wiener has described it:

> Only a small part of the monads are souls, the greater part being naked monads gifted with perception rather than apperception. Wiener [34c, p. 480]

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[13] A fuller discussion of the thought of Leibniz in relation to Wiener's cybernetics is given in Professor Gale's paper in these Proceedings.

These naked monads mirror the universe, but in a passive way, unable to integrate "the activity of mirroring into a self-conscious consciousness" [34c, p. 480]. As for the mirroring activity itself, Wiener perhaps hit the nail on the head when he wrote:

> This mirroring is best understood as a parallelism, incomplete it is true, between the inner organization of the monad and the organization of the world as a whole. The structure of the microcosm runs parallel to that of the macrocosm. Wiener [34c, p. 480].

How does this conception of the world fare when judged by the modern development of holography, which it should be emphasized is classical in that it follows from Maxwell electromagnetic theory of light and does not need the quantum theory of light?[14] Speaking of the Maxwell theory, Einstein wrote in 1905:

> One must, however, keep in mind that the optical observations are concerned with *temporal mean values* and not with instantaneous values, and it is possible, in spite of the complete experimental verification of the theory of diffraction, reflection, refraction, dispersion, and so on, that the theory of light that operates with continuous spatial functions may lead to contradictions with observations if we apply it to the phenomena of the generation and transformation of light. [Einstein (1905), pp. 544-545] (emphasis added)[15]

This thought on optical observation, with an explanation of how these "temporal mean-values" are measured, reappears in what Wiener wrote in 1929:

> One of the remarkable things about light is that the quantities which are

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[14] In fact Planck's constant h plays absolutely no role in Gabor's work.

[15] Physicists often insist on using the term "light" for that bandwidth of radiant energy which becomes light where it interfaces the biological retinal surface. Until an interface, biological or artifactual, occurs, the laws governing radiant energy are not those governing perceived light. By analogy, take an experience at the shore: Out in the ocean one can bob up and down with the water molecules by means of which the waves are transmitted. But when the waves interface with the shore, breakers occur, turbulence characterizes the resultant. The breakers with their whiteheads constitute a different phenomenon from the ocean beyond them. This insight is pursued by Wiener in the quotations that follow.

> primarily introduced in the Maxwell theory are not observed; at any rate, in the case of moderately high frequencies. The Maxwell equations concern the electric and the magnetic vector. Our optical observations deal with the blackening of a photographic plate or a measurement by a photometer, or the determination of the intensity of light with a photoelectric cell, or with the estimation of this intensity by the naked eye, or other measurements of the same general sort. Every optical observation terminates in this manner. [29c, p. 525]

But these thermodynamic transformations (often chemical reactions) to which the images are subject, can yield the "temporal mean values" only by destroying phase relationships. As Wiener noted in 1930 " . . . the interposition of a ground-glass screen or photographic plate . . . will destroy the phase relations of the coherency matrix of the emitted light, replacing it by a diagonal matrix with the same diagonal terms" [30a, p. 194]

It would seem then that were we to be able to examine the universe without recourse to such photometric processes, we would witness a hologram, that is, a huge interference pattern embodying all phase relations as in our example of the surface of a pond. In this so-called *implicate order* (to use a term due to D. Bohm), each organism, like a Leibnizian monad, re-presents the universe, and the universe reflects, in some manner, the organism that observes it. The perceptions of an organism cannot be understood without an understanding of the nature of the physical universe and the nature of the physical universe cannot be understood without an understanding of the perceptual process.

From the discussion in this and the earlier section, it would appear that the insights we have gained into the nature of the brain is broadly supportive of the Leibnizian point of view. When we bring to bear the new insights offered by quantum mechanics since the mid-1920's, the Leibnizian position gets significantly reinforced, but remarkably in a way in which the space-time and spectral perspectives get reconciled and appear to be no more divisive than the two faces of the same coin. This occurs via Planck's constant h, which opens up a bridge between space-time locatable concepts such as mass and energy and undulatory concepts such as frequency, wavelength, amplitude and phase.

7. The Place of Quantum Mechanics in Neuroscience

It is the very essence of the de Broglie-Schrodinger wave mechanics to claim for both matter and radiation the validity of the Planck-Einstein equations

$$mc^2 = h\nu, \qquad p = h/\lambda,$$

where m, E, p are the relativistic mass, energy and momentum of the photon or electron, and ν and λ are the frequency and wave length of its de Broglie waves. This then is the bridge between particle and wave, between mass and energy.

The ubiquitous role of quantum mechanics in neurobiology is obvious. Every time a photon enters the eye, an energy transaction obeying the law $E = h\nu$ takes place. The last 50 years have increasingly revealed that the role played by quantum mechanics in all of biology is significant. As Schrodinger wrote in 1946, "The mechanism of heredity is closely related to, nay founded on the very basis of quantum theory" (Schrodinger 1946, p. 47)

The possibility that processes in the brain's connection web may result in the transmission of photons of frequencies in the 10^{13}Hz, i.e. far-infrared range, was suggested by Fernandez-Moran in 1951, and has been increasingly borne out. In 1960 Wiener wrote:

> . . . the active bearer of the specificity of a molecule may lie in the frequency pattern of its molecular radiation, an important part of which may lie in the infrared electromagnetic range or even lower. [60g, p. 52]

Since the late 1960's Fröhlich's researches have confirmed collective behavior of assemblies of biomolecules resulting in long-range coherent radiation in the 10^{11}Hz range. And in the 1980's Adey suggested that coherent infrared radiation could be the basis of intracellular signaling and energy transfer over short distances. The quantum role is further addressed in the papers of Jibu, Yasue and Pribram (1993; 1996).

We must, however note that the *phase* of the undulations is conspicuously absent from the Planck-Einstein equations. To an extent this missing phase is restored in the researches of Fröhlich by virtue of his emphasis on coherence. But the tendency in quantum mechanical circles has been to ignore the phase of the de Broglie wave, and attribute significance only to its frequency, wavelength, and the non-negative square of its amplitude. Aside from a few great physicists such as Born, Dirac and Feynman, the common attitude has been to dismiss rather naively the de Broglie wave as a "mathematical tool."

It was the pioneering thought of Haldane (1934) that *the full-fledged de Broglie wave (with frequency, wavelength, amplitude and phase) is involved in all phenomena in the universe*, and thus the phase of the de Broglie wave is most germane to the understanding of cognitive processes. More precisely, what Haldane proposed was that the resonances of the de Broglie wave systems of highly organized material systems constitute their potential for "mental" prowess. His pithy paper (Haldane 1934) therefore merits a brief digression on our part.

The central theme of Haldane's paper is that the wave-mechanics of de Broglie and Schrodinger can explain the phenomena of both life and mind. He admits as limiting extremes the billiard-ball atomism of Lucretius and Newton on the one hand, and, on the other, the ideal world of Plato, these limits being attained as the mass-energy of the system is allowed to tend to zero or infinity, respectively. The fact that the universe is in-between these extremes is what makes life and mind possible. Recall in this regard, that posterior and frontal lobe stimulation of the brain can bring about tendencies toward these extremes of conscious processing (Pribram 1991; Lecture 10).

Haldane's paper is described in Chapter 10, Section D, of Masani's book (1990). The following is an adaptation of Pages 123-124 in it. Living organisms self-regulate, self-repair and self-reproduce, i.e. act as organic units in seeming defiance of the laws of physics and thermodynamics. To incorporate the living organism into science adding holistic postulates of one sort or another had been proposed by vitalists. Haldane points out that the atoms of physics also exhibit an organic unity. For instance, they quickly "repair" the loss of an electron by picking up another -- a behavior that the Rutherford, Bohr theories of the atom in the 1910's could not explain. Physicists healed this breach not by adding holistic postulates to these theories, however, but by discovering the intrinsic holism of wave-mechanics (ca. 1923). The de Broglie, Schrodinger theory was able not only to account for the observed atomic behavior, but to reveal the existence (then unknown) of two isomers of the hydrogen molecule. In his paper Haldane claims that this wave-mechanics serves to explain biological and psychological facts that were a mystery from the standpoint of classical physics and chemistry. As Haldane writes:

> In a degenerate system degrees of freedom are lost because certain periodic systems oscillate together instead of independently. This resonance gives rise to various observable phenomena. It is responsible for certain terms in the energy of a material system. As the resonators are removed from one another, the energy falls off very rapidly. Haldane (1934), p. 98.

Haldane points to some biological phenomena that exhibit the same sort of behavior. (a) During reproduction the gene loses its identity: it is hard to tell parent from daughter. (b) Quantum-mechanical resonance is behind the larger molecules, and larger building blocks of organic matter, e.g. the joining of amino acids that produces the protein molecule and chains thereof. Such resonance is what accounts for the self-regulatory and reproductive aspects of life.

Haldane draws an interesting analogy between crossing a *potential barrier* and purposive action on the part of brain-possessing organisms. Water in a cistern filled to one inch below the rim will not climb over the rim in order to spill out. But for a mouse placed in a cistern, who can see a piece of cheese lying outside, there is a positive probability that it will get out (or "leak") by climbing over the rim and jumping out. As with the quantum mechanical potential barrier, the probability of crossing will depend on the strength of the barrier, in our case the height of the cistern.

Haldane gives a simple explanation for this analogous behavior of mice and electrons: ". . . the electron can penetrate its potential barrier because the interference patterns of its wave mechanical system effectively extend beyond it" [Haldane (1934), p. 97]. Mice and men, and other objects too, have such non-local systems when transformed into 4-dimensional spatio-temporal terms, these systems extend into the future as well. It is this that enables cerebrally organized creatures to act with reference to future and distant events such as the joys of munching cheese or winning a tennis match or observing a solar eclipse, i.e. to act purposively. Thus Haldane brings mind into his quantum mechanical framework by interpreting it as a far-reaching wave mechanical system associated with the brain.

> In truth mind is permeated with internal contradiction at every level. We can reason about eternity but we are born and die. We measure in kiloparsecs and live in centimeters. We aspire and fail, we think and fall into error, we love and hate at once. A truly dialectical idealism would not meet these facts with remorse or denial, but with frank acceptance. Haldane (1934), p. 97

As Wiener has suggested [32c], [34c], the insights offered by quantum mechanics reinforces the Leibnizian view of the world. From a 1930 perspective Wiener wrote:

> Some of the Leibnizian monads mirror the world more clearly, some less clearly. This lack of clearness in mirroring is responsible for our impression that there is chance and indetermination in the world. Now, in the modern quantum theory, the indetermination which is an essential feature of the world, as represented in the ordinary four dimensions of time and space, is resolved, according to Heisenberg, if a sufficient number of additional, unperceived dimensions are superadded. This is the meaning of the five-dimensional theories of Fock and Klein, and is even more clearly brought out by the study of the problem of many bodies. This problem, which at present possesses no complete solution either from the standpoint of quantum theory or from that of relativity, even in the simple case of two bodies, can only be treated on the supposition that each electron carries with it is own complete space-time world. Thus, each electron possesses its own world of dimensions, which mirrors the many-dimensional universe of perfect cause and effect in an imperfect, four-dimensional, non-causal image. It is surely not fanciful to see

> in this a parallel to the Leibnizian monads, which live out their existences in a self-contained existence in pre-established harmony with the other monads, yet mirror the entire universe. [32c, p. 203]

And Wiener continued:

> And further, the more organized a system of elementary particles is, the less "naked" its electrons and other constituent elements, the better it mirrors the universe, and the better can we read back from our partial system to the universe at large. [34c, p. 480]

But Wiener's quantum mechanical interpretation of Leibnizian monadology is overshadowed by that offered unwittingly by Haldane in 1934. According to this interpretation, which rested securely on wave mechanics, every object is so-to-speak a monad, its materiality being supplied by its mass and its potential "spirituality" by its de Broglie wave system.

On the basis of such reasoning, the brain is seen to be the medium for the transformations that allow us to partake both of the "ideal" and the "material" -- the transformations into and out of the implicate order, in Bohm's terminology.

8. Conclusions and Tasks Ahead

The mind-brain ontology, developed in this paper is monistic in the sense of denying a duality between mind and matter (not in the sense of it being only one monad). According to this view, another class of orders lies behind the level of organization we ordinarily perceive. The ordinary order of appearances can be described in space-time coordinates. The other class of orders is constituted of fine-grain distributed organizations which can be described as potential in the Aristotelian sense because only after "radical" transformation is their palpability in spatiotemporal terms realized. When the potential is actualized, information (the form within) becomes unfolded into its ordinary space-time manifestation; in the other direction, the transformation enfolds and distributes the information much as this is done by the holographic process. Because work is involved in transforming, descriptions in terms of energy are suitable, and as the form on information is what is transformed, descriptions in terms of entropy (and negentropy) are also suitable. Thus, on the one hand, there are enfolded potential orders; on the other, there are unfolded orders manifested in space-time.

Left unaddressed by this explanation are two issues: 1) What is it that remains invariant when a transition is made between the various levels of the scientific hierarchy such as between atomic physics and chemistry, chemistry and membrane biology, membrane biology and cell biology, etc., and 2) What is the nature of the correspondence between the message in a computer program or musical score and their physical embodiments, i.e. the wiring of the computer and the arrangement of ink dots and lines on paper? I believe the answer to both the questions hinges on whether one concentrates on the order (form, organization) or the embodiments in which these orders become instantiated[16] (Pribram, 1986; 1993).

One has to separate superficial manifestations trans-formable into one another, and the deeper invariants such as the structure of DNA in the biological examples above which in-forms the transformations (Pribram 1996/In Press). For instance, among the instantiation of Beethoven's Sonata (Opus 111) are an initial composition (a mental operation completed while Beethoven was already totally deaf!) a score (a material embodiment) a performance (more mental than material) a recording on compact disc (more material than mental) and the sensory and brain processes (material) that make for appreciative listening (mental). But in the transitions from one instantiation to the next, a certain relation -- structure, in the Russellian sense, remains invariant. This invariant relation-structure is unaffected by the centuries of "performances, recordings and listenings;" It is the essence of Beethoven's Opus 111. For a detailed and sophisticated development of this thesis, see Arturo Rosenblueth's *Mind and Brain*, MIT Press (1970, Chapter 6).

As Rosenblueth points out, what remains invariant across all instantiations is abstract structure, "in-formation", the form within. Thus, according to this analysis, it is Platonic "ideals," interpreted as informational structure, that motivate the philosophical dialogue spawned by the information revolution (e.g. "information processing" approaches in cognitive science) and distinguishes this dialogue from the continuing dialogue between dualists such as Popper & Eccles (1977), materialists such as Dennett (1991) and mentalists such as Searles (1992) and Sperry (1980), a vestige of the now waning industrial revolution. The machine was then treated as dead-matter without a trace of mind in it. But there is a more penetratingLeibinizian view of the machine based on the functions of computers. This was well articulated by Wiener in the words:

> For us, a machine is a device for converting incoming messages into outgoing messages. A message, from this point of view, is a sequence of quantities that represent signals in the message. Such quantities may be electrical currents or potentials, but are not confined to these, and may be distributed

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[16] By *instantiation* of a universal (form or organization) is meant one of its reifications, i.e. embodiments (see Pribram 1971; 1991). For instance, *A*, 𝔄, A are instantiatians of the A design, which is universal.

> continuously or discretely in time. A machine transforms a number of such input messages into a number of output messages, each out put message at any moment depending on the input messages up to this moment. As the engineer would say in his jargon, a machine is a multiple-input, multiple-output transducer. [64e, p. 32]

To return to Platonic ideals and their relation to the information constituting a message, Haldane noted that Platonic ideas are limits of real ideas. Russell's relation-structures (1948) provide the manner by which these limits are attained. According to my perspective, in-formation conceived as negentropy and thus the structuring of massless bosonic radiant energy (see Pribram, 1986 for detailed argument) is neither material nor mental. This approach suggests that a scientific pragmaticism akin to that practiced by Pythagoreans and early Ionians[17], will displace mentalism and dualism as well as materialism as a central concern of philosophy. Both the ideal mathematical structures which are essentially mental and the material structures in which they are instantiated are "real" to me. Thus, by temperament, I need to be grounded in the nitty gritty of experimental and observational results as much as I am moved by the beauty of theoretical formulations expressed mathematically. In my opinion, therefore, the tension between idealism (the potential), and realism (the appearance) which characterized the dialogue between Plato and Aristotle, will replace that between mentalism and materialism. This change in tension will lead to a new surge of experimentation, observation and theory construction in the spirit of a Pythagorean pragmaticism.

Thus, an answer to the questions as to how mind becomes organized by brain rests on our understanding of the lessons of quantum mechanics and especially of that aspect which encodes the spectral domain, the implicate order. Although engineers daily use the spectral domain in radar, crystallography and tomography--wherever image processing is important--cognitive neuroscientists are, as yet, only barely acquainted with the pervasive nature of this order. It is now necessary to make accessible, both by experiment and by theory, the rules for "tuning in" on the implicate domain so that this domain can become more generally understood and scientifically validated. It is critical to our well-being that this domain be accepted as operating by virtue of those specific brain processes (see Pribram 1991, Lecture 10; Yasue, Jibu and Pribram 1991,

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[17] "The claim of the early Ionians that nature was intelligible was based on their view that the practical arts were intelligent efforts of men to cooperate with nature for their own good." (B. Farrington, 1961, p. 46.) This view was shared by C.S. Pierce and Wiener.

Appendices A-G) that allow us to resonate to universal orders as cognized by Leibniz, Haldane and Wiener and that we are apt to call spiritual.

Appendix: Gabor's elementary signals and logons

Gabor's pioneering efforts of 1946 addressed the problem of maximizing telecommunication across the then newly-laid Atlantic Cable. The problem arises because simple harmonic analysis is inadequate to deal with phenomena in which frequency itself fluctuates rapidly, e.g. the siren. Gabor has explained the inadequacy of the Fourier theory as follows:

> The reason is that the Fourier-integral method considers phenomena in an infinite interval, *sub specie aeternitatis*, and this is very far from our everyday point of view. Fourier's theorem makes of description in time and description by the spectrum, two mutually exclusive methods. If the term "frequency" is used in the strict mathematical sense which applies only to infinite wave-trains, a "changing frequency" becomes a contradiction in terms as it is a statement involving *both* time and frequency.
>
> The terminology of physics has never completely adapted itself to this rigorous mathematical definition of "frequency." In optics, in radio engineering and in acoustics the word has retained much of its everyday meaning, which is in better agreement with what Carson called "our physical intuitions." For instance, speech and music have for us a definite "time pattern," as well as a frequency pattern. It is possible to leave the time pattern unchanged, and double what we generally call "frequencies" by playing a musical piece on the piano an octave higher, or conversely it can be played in the same key, but in different time. Evidently other views have their limitations, and they are complementary rather than mutually exclusive. [Gabor (1946), p. 431]

From excerpts of Wiener's writings that I received from Masani, it is clear that Wiener was aware of "this paradox of harmonic analysis", as he called it, in 1925. Indeed, Wiener's writings on musical notation elucidates the words of Gabor on music that we just quoted:

> Now, let us see what musical notation really is. The position of a note vertically on the staff gives its pitch or frequency, while the horizontal notation of music divides this pitch in accordance with the time. The same notation contains the indication f the rate of the metronome, the subdivision of sound into whole notes, half notes, quarter notes, etc., the various rests, and much else besides. Thus musical notation at first sight seems to deal with a

system in which vibrations can be characterized in two independent ways, namely, according to frequency, and according to duration in time.

A finer assumption of the nature of musical notation was that things are not as simple as all this. The number of oscillations per second involved in a note, while it is a statement concerning frequency, is also a statement concerning something distributed in time. In fact, the frequency of a note and its timing interact in a very complicated manner.

These considerations are not only theoretically important but correspond to a real limitation of what the musician can do. You can't play a jig on the lowest register of the organ. If you take a note oscillating at a rate of sixteen times a second, and continue it only for one twentieth of second, what you will get is essentially a single push of air without any marked or even noticeable periodic character. It will not sound to the ear like a note but rather like a blow on the eardrum. [56g, p. 105]

In 1946 Gabor put this "paradox of harmonic analysis" to constructive use in signal theory by the simple device of seeking the signal f on the time -- axis ($-\infty$, ∞), which turned the inequality (1) in Section 4 into an equality. More accurately, consider the more general form of (1)

$$\int_{-\infty}^{\infty} |(t-a)f(t)|^2\,dt \cdot \int_{-\infty}^{\infty} |(\lambda-b)\hat{f}(\lambda)|^2\,d\lambda \geq \frac{1}{4}\int_{-\infty}^{\infty} |f(t)|^2\,dt \cdot \int_{-\infty}^{\infty} |\hat{f}(\lambda)|^2\,d\lambda.$$

It can be shown that equality prevails in this when and only when f is of the form

$$f(t) = Ce^{-(t-a)^2/2r} \cdot e^{-ibt}, \qquad for \quad t\ real,$$

where C and r are real constants, and $r \geq 0$. For a suitable normalization the constant C becomes $(2r/\pi)^{1/4}$. Thus we get time-signal s f depending on 3 parameters, a, b and r.

Gabor called each such function $g_{a,b,r}$ given by

$$g_{a,b,r}(t) = \left(\frac{2r}{\pi}\right)^{1/4} e^{-(t-a)^2/2r} \cdot e^{-ibt}, \qquad for \quad t\ real,$$

an elementary function, and believed that this 3-parameter system $\{g_{a,b,r}$: a, b real

& r ≥ 0} is more fundamental for the purpose he had in mind than the familiar one-parameter system

$$\{e_\lambda : \lambda \; real\} \qquad where \quad e_\lambda(t) = e^{i\lambda t}$$

of harmonic analysis.

Gabor suggested that time-signals be represented by lines in a *time-frequency* (t,ν) *plane*. The signal $e_{2\pi\nu_0}$, where the frequency ν_0 is constant, is represented by the line $\nu = \nu_0$ parallel to the t-axis. The signal δ_{t_0} with one-point support at t_0, and so with frequency band $(-\infty, \infty)$, is represented by the line $t = t_0$ parallel to the ν-axis. (Figure 1.) It is clear that in this "plane" only lines parallel to the t and ν-axis are allowed, with the result that all diagrams are made up of rectangles with sides parallel to these axes.

Thus a signal of time-span $[a,b]$ and frequency band $[c,d]$ made up of pulses, will be represented by the diagram in Figure 2.

It is clear that a rectangle in the plane giving one datum of information on time and one on frequency could serve as a "unit of information", this *structural information*, not to be confused with the Shannon-Wiener probabilistic information. It is also clear that the best unit rectangle is the one for which $\Delta t \cdot \Delta\nu$ = the constant, obtained from the time-frequency equality. Gabor called this the "quantum of information" because of the similarity of the mathematics he used to that used by Heisenberg in defining a subatomic quantum, and he named it the *logon*. It corresponds to the *bit* in the Shannon-Wiener theory.

The simplest example of a logon-diagram in the time-frequency plane is a sheet of music -- only the round notes have to be turned into rectangles and shaded. The term "information plane" is most fitting, since the sheet gives the interpreter exact information as to what to do.

As stated in Section 4, to deal with the patterns in the connection web, it is necessary to partition the 5-dimensional space-time frequency plan (x, y, z, t, λ) into Gabor "logons".

Fig. 1

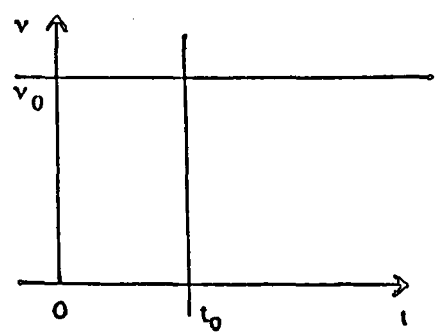
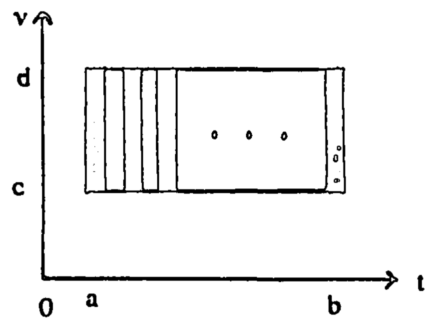


Fig. 2



Acknowledgement

Many thanks are due to Professor Masani – not only for making available his excellent publications and providing the equations used in this manuscript, but for his persistent critique and insightful help in putting together this essay. Thanks also to Shelli Meade, who typed and typed and typed yet again the innumerable revisions.

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