Vortex Model of the Brain:
- The Missing Link in Brain Science? -

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Introduction

There is no doubt that discrete neuronal networks play an essential role in brain function. Nevertheless, many fundamental questions regarding how the brain works remain unanswered. What is the neuronal substrate of consciousness? Why do anesthetic effects diminish at higher atmospheric pressure? How can purely endogenous processes be initiated? These are some examples. In spite of concerted effort by the world's preeminent neuroscientists, no complete theory of brain function has thus far been offered. This void strongly suggests that there must be a *missing link* in the current fundamental concept of how the brain works.

All modern theories eventually require confirmatory proof based on hypothesis-driven experimental results. However, it is often difficult to formulate such a hypothesis in a science which is already highly developed. The successful formulation of the best hypothesis itself should reflect the final accomplishment in the field. In contrast to other fields of science, biological science still remains heavily phenomenology oriented. This tendency toward a description based science has likely served as a major obstacle in the derivation of a global hypothesis of brain function. On the other hand, purely mathematical hypotheses introduced by scientists in non-biological fields, such as mathematics, physics, and engineering, have often failed to provide biological realization. It is clear that the world of neuroscience is in desperate need for a truly multi-disciplinary approach to solving its challenges.

Any model of the brain has to be: (1) completely compatible with all phenomenology described; (2) consistent with principal rules of the universe and phylogeny; and (3) preferably in the form of simple mathematical equations. I present here such a model, the *Vortex Model* of the brain.

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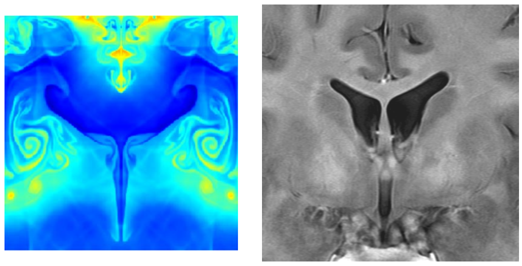
Axiomatic Bases

Axiomatic Basis I: Brain self-organizes based on the rule of free convection.

This axiomatic basis is the starting point of the *Vortex Model*. I was first inspired by the possibility of utilizing a specific differential equation to model the shape of the brain in 1989 when I encountered the pictorial display of the fate of a plume published in Science as an example of a new simulation algorithm, the piecewise parabolic method (PPM) (Cipra, 1989). It was not until ten years later that I got the opportunity to confirm the concept using an Origin 2000 for running the simulations especially aimed at the shape of the brain (Nakada and Suzuki, 2000). The detailed description of the study is presented elsewhere[2]. The following is a brief presentation.

Suppose that a fluid is at temperature $T+\theta$, where T is uniform but θ is not. Free convection associated with a thermal core of steady temperature is given by the Boussinesq equations:



Simulation **MRI**

Figure 1

A representative example of the results of the simulation for free convection (see Appendix). Due to imperfection of the selected initial conditions, the simulated image (Simulation) is not "perfectly identical" to the actual brain shown by magnetic resonance imaging (MRI). Nevertheless, the surprising similarities in detail is demonstrated, clearly indicating that brain organization indeed follows the self-organization schema of free convection.

$$(\mathbf{v}\cdot\nabla)\mathbf{v} = -\nabla\frac{p^*}{\rho} - \beta\theta\,\mathbf{g} + \nu\Delta\mathbf{v}$$
$$\mathbf{v}\cdot\nabla\theta = \chi\Delta\theta$$
$$\nabla\cdot\mathbf{v} = 0$$

where $\chi = {}^{\kappa}\!/_{\rho c_p}$ represents thermometric diffusivity, β, thermo-expansion coefficient, and ν, kinetic viscosity. The equations stand to an effectively incompressible fluid of uniform density ρ, and the gradient of excess pressure is given by $\nabla p^* = \nabla p + \rho\mathbf{g}$ (Faber, 1995, Landau & Lifshitz, 1987). With proper initial conditions, "the fate of a plume" based on the above differential equation effectively outlines the shape of the brain (Figure 1) (see Appendix). The result is not totally surprising since it has been believed that the process of self-organization based on certain rules should be the key element to defining the highly complex brain networks (see Corollaries below). Additionally, this fact leads us to the important conclusion: the shape of the human brain is *not accidental*. Rather, it exhibits specific physical significance of the creation of a *virtual sphere in accordance to convective flow* (Figure 2).

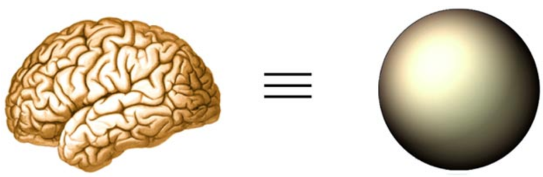


Figure 2

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[2] Nakada T. and Suzuki K.: Human brain and self-organization. (Submitted)

An important consequence of the fact that the brain is in actuality a virtual sphere is that it ensures equivalence within the entire cortex of any of the columns, the basic units of brain organization, in an orientation perpendicular to the surface of the brain (Figure 3). This significance will be further elaborated later.

Axiomatic Basis II: Astrocytes have all the structural significance necessary for anatomical realization.

The most important factor in a biological hypothesis is firm biological realization. The human species has created various state-of-the-art machines. The principle of any human created technology can, however, be found in nature. Even though the available materials in the biological world are significantly limited, Mother Nature has nevertheless succeeded in creating virtually all conceivable functional units. She has accomplished this intuitively impossible job so well by perfecting two basic rules, namely, sophistication of the structure/shape and sophistication of the steady state condition (homeostasis). Therefore, in the biological world, anatomical realization for a given functionality represents not only the necessary condition but also virtually the sufficient condition to prove the hypothesis.

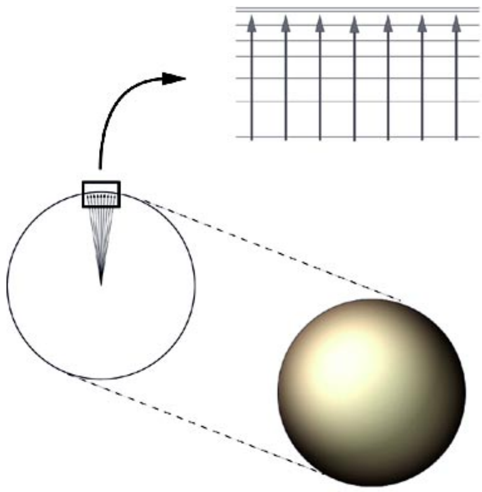

Figure 3

Astrocytes possess all the structural significance necessary for anatomical realization of the *Vortex Model* presented below. These properties are schematically summarized in Figure 4. The functional significance of these structures will be elaborated further below.

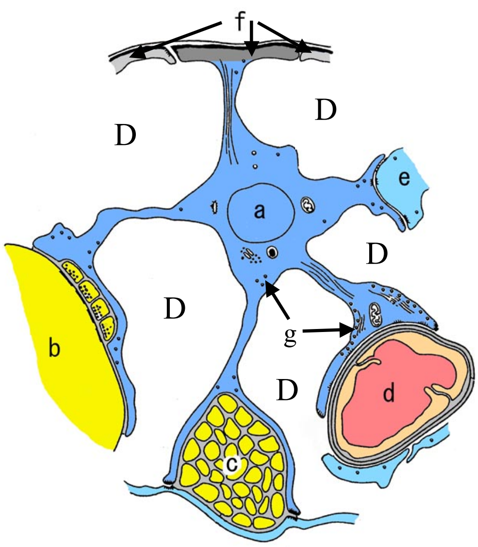

Figure 4

Schematic presentation of an astrocyte and its principal processes. Modified and redrawn based on the figures from Hirano, 1999 and Sasaki, 1999. Astrocytes possess all the structural significance necessary for anatomical realization of the hypothesis. The key elements include: (1) electron rich layer formed by the principal processes just under the pia mater; (2) two compartments of extracellular spaces segregated by principal processes; and (3) assemblies. "D" indicates "dry area", the second extracellular space. See text for details. a: astrocyte, b: neuron, c: axon bundle, d: vessel, e: neighboring astrocyte, f: electron rich layer, g: assemblies.

Elaboration of the Hypothesis

Entropy-Vortex Wave and Cortical Information Processing

Axiomatic Basis I indicates that the shape of the human brain is *not accidental*. Rather, it possesses specific physical meaning in the creation of a *virtual sphere in accordance to convective flow.* An important consequence of this fact is that it ensures equivalence of any of the columns within the entire cortex in an orientation perpendicular to the surface of the brain and a steady flow in the direction from the core to the surface (Layer VI to I) in all the columns (Figure 3).

To demonstrate the functional significance of such an organization, here, the effects of a minor perturbation on such a steady flow will be elaborated (Faber, 1995, Landau & Lifshitz, 1987).

Euler's equation is given by:

$$\frac{\partial \delta \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\delta \mathbf{v} + \frac{1}{\rho} \nabla \delta p = 0$$

where δv and δp represent small perturbations in velocity and pressure, respectively.

Similarly, conservation of entropy and the equation of continuity give:

$$\frac{\partial \delta s}{\partial t} + \mathbf{v} \cdot \nabla \delta s = 0$$

$$\frac{\partial \delta p}{\partial t} + \mathbf{v} \cdot \nabla \delta p + \rho c^2 \nabla \cdot \delta \mathbf{v} = 0$$

where $\delta \rho = \frac{\delta p}{c^2} + (\frac{\partial \rho}{\partial s})_p \delta s$ and c represent sound velocity.

For a perturbation having the form $\exp[i\mathbf{k} \cdot \mathbf{r} - i\omega t]$, one gets:

$$(\mathbf{v} \cdot \mathbf{k} - \omega)\delta s = 0$$

$$(\mathbf{v} \cdot \mathbf{k} - \omega)\delta \mathbf{v} + \mathbf{k}\frac{\delta p}{\rho} = 0$$

$$(\mathbf{v} \cdot \mathbf{k} - \omega)\delta p + \rho c^2 \mathbf{k} \cdot \delta \mathbf{v} = 0$$

This result prescribes that there will be two types of perturbations, namely, entropy-vortex wave and sound wave as defined below.

Entropy-Vortex Wave

$$\omega = \mathbf{v} \cdot \mathbf{k}$$
$$\delta s \neq 0$$
$$\delta p = 0$$
$$\delta\rho = \left(\frac{\delta\rho}{\delta s}\right)_p \delta s$$
$$\mathbf{k} \cdot \delta\mathbf{v} = 0$$
$$\nabla \times \delta\mathbf{v} = i\mathbf{k} \times \delta\mathbf{v} \neq 0$$

Sound Wave

$$(\omega - \mathbf{v} \cdot \mathbf{k})^2 = c^2 k^2$$
$$\delta s = 0$$
$$\delta p = c^2 \delta\rho$$
$$(\omega - \mathbf{v} \cdot \mathbf{k})\delta p = \rho c^2 \mathbf{k} \cdot \delta\mathbf{v}$$
$$\mathbf{k} \times \delta\mathbf{v} = 0$$

For the purpose of brain modeling, the following points should be emphasized: (1) for entropy-vortex wave, $\delta s \neq 0$ and $\omega = \mathbf{v} \cdot \mathbf{k}$; and (2) for sound wave, $\delta s = 0$. These conditions predict that a perturbation can produce entropy changes ($\delta s \neq 0$) and, hence, information processing (Cover & Thomas, 1991, Arbib, 1995) and create entropy-vortex waves. The fact $\omega = \mathbf{v} \cdot \mathbf{k}$ ensures that an entropy-vortex wave, which carries newly processed information, travels only in the direction identical to the original flow. In the case of the brain where the original flow is always perpendicular to the surface of the brain, this flow is in the direction parallel to the columnar arrangement from layer VI to I (Figure 5). The velocity of the sound wave is subsonic and, hence, will travel in all directions[3]. However, a sound wave does not carry any new information ($\delta s = 0$).

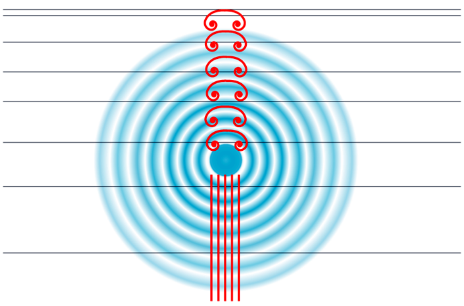

Figure 5

Minor perturbation results in formation of entropy-vortex wave and sound wave. The former travels in the direction identical to the original flow, whereas the latter in all directions. An entropy-vortex wave carries newly processed information ($\delta s \neq 0$), while s sound wave does not ($\delta s = 0$).

[3] Sound waves travel faster in water than in air. So a sound wave perturbation is likely to enter the “wet” area immediately.

The Astrocyte Matrix Creates a "Dry" Compartment

In spite of intensive investigation, the precise functions of astrocytes are thus far not entirely understood. Astrocytes are a cousin of neurons. Both astrocytes and neurons evolve from the identical stem cells. It is hardly conceivable that the sophisticated architectural structures of astrocytes are simply supportive in nature. It is credible, although unorthodox, to advance the notion that astrocytes play an active role with respect to the function of information processing.

Astrocyte networks are generally believed to play a key role in the formation of the blood brain barrier (BBB). Nevertheless, the astrocyte network *per se* is not the BBB itself. The principal elements of the blood brain barrier (BBB), the structure involved in gating substrate transport, are believed to be endothelial cells of the small blood vessels and not astrocytes[4]. It is clear that astrocyte networks do not represent the principal structural components of the BBB (Kettenmann & Ransom, 1995). Rather, astrocytes influence endothelial cell specialization in establishing the BBB. Such a regulatory role cannot justify the presence of the well described dense astrocyte networks.

Because of the scarcity of extracellular space in the brain, the astrocyte cell body *per se* was once thought to play the role of "extracellular" space. Since the intracellular environment of astrocytes is cytoplasmic in nature, the astrocyte cell body cannot replace the extracellular space of the brain. However, astrocyte processes are obviously involved in establishing extracellular fluid compartments and maintaining these environments, e.g. the surroundings of the synaptic areas and nodes of Ranvier[5] (Figure 4). These extracellular spaces, containing extracellular fluid, are created by the primary processes of astrocytes which effectively serve as a seal. Astrocytes therefore appear to be actively involved in compartmentalizing the extracellular space in the brain (Kettenmann & Ransom, 1995).

Why is extracellular space compartmentalization necessary? It is highly unlikely that the brain requires *two* independent extracellular spaces of identical composition. Given that astrocytes create a specific extracellular compartment using their primary processes, how does this compartment differ from conventional extracellular space? There must be a rather drastic difference between the astrocyte established extracellular compartment and the conventional extracellular space.

As is commonly encountered in biology, the astrocyte matrix may play a dual role, namely, a physical-structural as well as a functional role. Let's first consider the physical role, namely, the role of astrocytes as supportive structure. This exercise may yield clues about its functional role. What is the advantage of having a matrix-style support structure? A well known biological example of a matrix support system is bone. Compared to solid bone, bone which consists of matrix formation may be lighter in weight when filled with low specific gravity material such as air. The structure also is much more efficient in preserving structural integrity. Could the astrocyte matrix also be effecting a lighter brain by filling the space with lower specific gravity material? Such a compartment would be drastically different from the compartment comprising conventional extracellular space. I refer to this compartment as the "dry" space (relatively speaking) in comparison to the conventional composition of extracellular fluid (Figure 4). Is there any anatomical structure within the astrocyte to support this concept? The answer is yes. The astrocyte assembly fulfills this requirement.

Astrocytes contain a curious structure termed assembly. Recent molecular genetics have

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[4] The primary processes of astrocytes cover 80-90%, not 100 % of blood vessels.

[5] Secondary processes of astrocytes form broad sheet-like structures which do not attach to any specific structures.

shed light as to the functional identity of this peculiar structure. There is substantial evidence indicating that the astrocyte assembly is identical to aquaporin 4, a water channel found in great abundance in the collecting tubules of the kidney (Yang et al., 1996, Sasaki, 1999). This function strongly suggests that one of the specific functions of astrocytes is related to the control of water contents.

If indeed astrocytes regulate water transport, astrocytes can be expected to be involved in establishing compartments which have substantial differences in water contents. Here, I propose that one of the compartments created by astrocytes is a "dry" area in contrast to the wet area of conventional extracellular fluid[6]. It should be clearly emphasized that this dry area is by no means totally dry in the physical sense. Rather, it implies the condition where water contents are substantially lower than in ordinary extracellular space. To be compatible with the hypothesis, the degree of dryness should be at the level where the Reynolds number of the contents (fluid) should be sufficiently high to produce steady flow as convection[7].

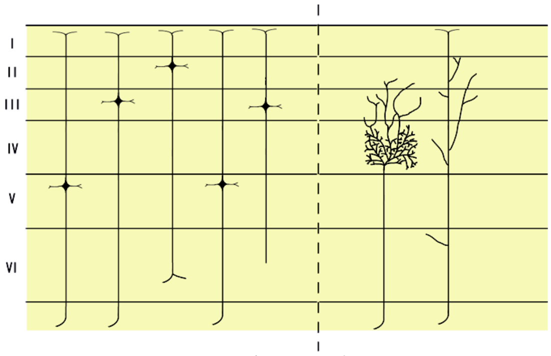

Figure 6

Schematic representation of cortical outputs (left) and inputs (right). Modified and redrawn based on figures presented by Parent, 1996.

Electron-dense Layer and Dendritic Ramification (ELDER) forms a Synapse-like Unit

Another intriguing anatomically well described but functionally poorly understood structural aspect of astrocytes is the electron dense layer of the principal processes[8]. This layer is formed by those astrocyte processes lining up immediately underneath the subpial basement membrane, just at the surface of the brain (Figure 4). What indeed could be their functional significance?

In daily life, a common example of an electron rich plate in an electrical

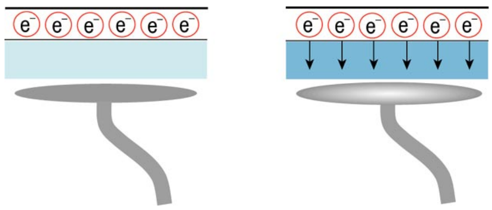

Figure 7

Schematic presentation of the ELDER system. With the permittivity lower than threshold (left), current does not occur (rest). The higher water density increases permittivity. Once threshold is reached (right), current will be introduced (excitation).

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[6] The presence of a "third" space has been implicated in various contexts including interstitial fluid flow (Cserr & Ostrach, 1974, Rosenberg et al., 1980). However, it has never been formally proposed. It is extremely difficult to confirm this dry compartment which exists only as a micro-environment in the live, functioning brain. This difficulty itself is supportive evidence of the existence of this compartment.

[7] There are several reasons to believe that CO_2 would be the primary gas within the dry area. High concentrations of carbonic anhydrase in oligodendroglia may indeed reflect this functionality.

[8] Basic physics tells us that the presence of a static electric field implies the presence of dielectric material. The implication of such a material represents another piece of supportive evidence for the presence of a dry area, where, this time, dry also refers to low electric permittivity.

device is the source of electrons in the heated filament of the vacuum tube. It appears intuitive that the electron dense layer lining the entire inner surface of the pia matter (and, hence, the surface of the brain) is part of an apparatus for current generation which emits electrons inwards[9].

Layer I of the cortex (molecular layer) contains the terminal dendritic ramifications of the pyramidal and fusiform cells from the deeper layers (Figure 6). Accordingly, I propose that the electron dense layer formed by the primary processes of astrocytes and dendritic ramifications of pyramidal and fusiform neurons constitute a synapse-like unit, I term ELDER.[10] The electron dense layer plays the role of synaptic button, while the dendritic ramifications that of receptor (Figure 7). How does transmission occur? The answer is by turbulence created by entropy-vortex waves detailed below.

The Hypothesis: the Vortex Model of the brain

According to the hypothesis, in addition to conventional neuronal networks, the brain has another information processing system, namely, entropy-vortex wave based cortical processing. The system is based on steady fluid (gas) flow in the form of a free convection pattern.

The convection schema has two possible discrete patterns for *self-organization* (Figure 8). The first pattern is represented by the case of a heated solid body immersed in fluid. Such a system shows a relatively large scale free convection. The second pattern is represented by the case of fluid within a shallow space between two parallel plates of different temperatures. Such a system shows a Bénard type of convection (see Appendix).

In the context of the free convective self-organization schema, the reticular activation system (RAS or reticular formation) and its connectivity within thalamic regions are likely to play the primary role of a solid body with steady temperature for generating convective flow. Neuronal impulses arriving at the mesencephalic reticular formation have eventually to be converted into heat[11]. This heat is the likely

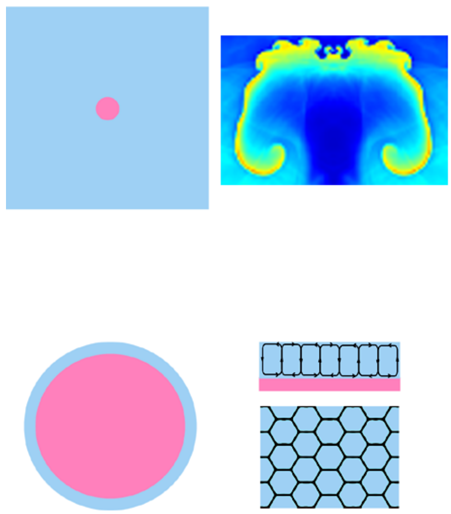

Figure 8

Two types of self-organization based on convection schema: free convection (above) and Bénard type convection (below). The brain appears to utilizes both schemas. Strictly speaking, the primary force which drives a Bénard type of convection in biological systems is likely to be the release of surface free energy. Therefore, this type of convection should be referred to as Marangoni convection, the significance of which is a hexagonal shape of the convection cells as shown here.

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[9] The direction from the subpial area (superficial cortex) toward the deep cortex.

[10] ***E***lectron-dense ***L***ayer and ***DE***ndritic ***R***amification.

[11] The RF receives a large quantity of neuronal impulses (energy) while having little output. For example, more than 40% of the pain fibers arising from the spinal cord terminates within the RF. The abundance of pain fibers

energy source for the heated solid body. The convective flow ensures a steady fluid (gas) flow in the brain. The route of fluid (gas) flow in the cortex is secured by the astrocyte network forming the dry extracellular compartment. Brain shape, which follows a free convection pattern, ensures steady flow in all cortical columns to be equivalent qualitatively as well as quantitatively over the entire cortex. Neuronal input (energy in electrical form) to the deep layers of the cortex introduces a small perturbation within the steady flow of the column as illustrated in Figure 5. The resultant vortex-entropy wave travels together with the steady flow, namely, identical columns, and reaches the molecular layer.

The second convective self-organization described previously is represented by the most superficial layer of the cortex, which forms a shallow shell (dry area) filled with fluid (gas) between two parallel plates. In this schema, the electron dense layer of astrocyte processes constitutes the plate with the lower temperature, whereas the remainder of the brain the higher temperature plate. This convection system shows a Bénard type of convection which creates a well known *self-organization* pattern, namely, *convection cells* (see Appendix). This multiple-cell oriented self-organization pattern is highly consistent with cellular automata (see below). The self-organized dry area defines the baseline electric permittivity of the ELDER unit (Figure 7).

The turbulence generated by the vortex reaches the surface area and alters the condition of convection cells and hence the electric permittivity of the extracellular dry area between the electron dense layer and dendritic ramifications of the ELDER unit. At a certain level of water density, electric permittivity reaches the threshold and electrons are released. The release of electrons results in formation of a dendritic impulse. The turbulence may facilitate or suppress the baseline ELDER discharge.

Corollaries

Thermal Convection as a Prototype of Self-Organization Phenomena

Genes represent the principal blue print of all biological organisms on this planet coding for both structural and functional proteins[12]. Because of this, it is intuitively believed that all the detailed structural traits of an organism are genetically determined. Such is not the case. Consider the fact that the human cortex contains more than 10^{14} synapses. Even without regard to the size of the genome, one can easily deduce that a deterministic blueprint for the connectivity of such an enormous number of networks is totally unrealistic, if not ridiculous. As is the case for the physics world, determinism should be abandoned when one considers the principles of how the brain works. The conclusion naturally derived from the accumulated knowledge in science is that Mother Nature is likely to utilize principal rules instead of complete deterministic descriptions to create a desired structure: the principle rule of *self-organization*.

Thermal convection is often treated as a prototype of self-organization phenomena (Davies, 1989, Arbib, 1995). As shown in Axiomatic Basis I, the first type of *self-organization* seen in the brain is free convection, which defines the general configuration of the brain. According to

within the RF also illustrates how pain is a most effective stimulation for arousal.

[12] Except in some rare exceptions such as prions.

this schema, the heated solid body generating the force of convection flow is located deep within the *virtual sphere*. For the brain, the mesencephalic reticular formation and its connections within the thalamic area perform this role (Figure 8).

Another well known example of convective *self-organization* that appears to occur in the brain is in the form of Bénard convection (see Appendix). The surface of the superficial layer (Layer I) of the brain where ELDER is found can be regarded as a thin fluid containing shell covering a large spherical solid (the brain itself). It is immediately apparent that the core would have a temperature higher than the superficial layer. This temperature differential fulfills the condition to create a *Bénard convection*. *Self-organization* of the fluid (gas) within this thin shell area, here referred to as *lattice-gas shell*, results in the formation of convection cells as illustrated in Appendix. In biological systems, the primary force which drives this type of convection is likely to be the release of surface free energy rather than gravitational potential energy as is the case for the shallow layer of water covering the earth. This type of *Bénard convection* is often referred to as *Marangoni convection*. The significance of the latter is that the shape of the self-organized convection cells is invariably *hexagonal* (Figure 8).

Cellular Automata to Neuronal Network: Dual Shell Processing

The functional aspects of the *Vortex Model* described so far can be further simplified as illustrated in Figure 9. In this schema, the cortex has dual processing shells, namely, the *lattice-gas shell* formed by the ELDER component with *Marangoni hexagonal convection cells* and the *neuronal network shell* formed by conventional cortical networks.

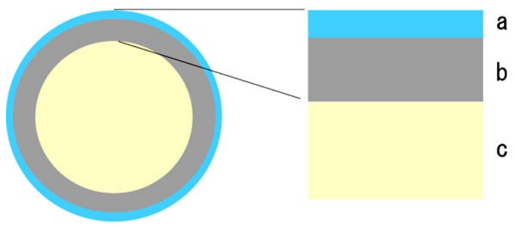

Figure 9

Schematic presentation of the dual processing shell system. a: lattice-gas shell, b: neuronal network shell, c: white matter and other deep structures.

The thickness of convection cells can be conceptually treated as the axis representing the state of the cell (up vs. down). In turn, the *lattice-gas shell* can be considered as a two-dimensional sheet composed of an astronomical number of identical Ising neurons (cells) physically connected to neighboring cells without the use of axons. This structural configuration is highly consistent with cellular automata (Arbib, 1995, Copard & Droz, 1998). The output of this *lattice-gas shell* is passed onto the neuronal network shell where deterministic connectivity (neuronal network) takes over the main role in information processing in the brain. In other words, information is first processed using programmable "matter" (cellular automata) which has a significantly higher degree of freedom. Subsequently results are passed onto the programmable "machine" (neuronal network) which has a much lower degree of freedom but a better reliability in executing discrete tasks. In this context, the ELDER system plays the role of connecting the non-deterministic information processing system to the deterministic system.

Boldly speaking, I conclude that the fundamental unit which makes the human, and perhaps other mammalian, brain cortex unique is the *lattice-gas shell* part of the brain.

Critical Point Phenomena: Universality and Re-normalization

In the early 1970's, Kenneth Wilson (1982 Nobel prize laureate for physics) published a series of papers opening up a new field of physics now generally referred to as critical point physics. It is far beyond the scope of this short paper to describe this highly innovative concept in detail. Nevertheless, it cannot be overemphasized that the conceptual revolution that Wilson initiated indeed represents the beginning of a new era reflecting the final stage of science: *principal rules for everything*.

The key words of the concept are *universality* and *re-normalization*. The *universality* concept provides strong motivation for studying physical phenomena which possess (a) critical point(s) at which apparently greatly disparate physical systems actually demonstrate similar essentials. There are generic problems which are universal to a whole class of problems in different systems in physics, from turbulent flow to gauge theory. The *re-normalization group theory* provides technical tools with which to solve actual problems in the tangible world.

The concept of the *re-normalization group* provides scaling of configurations (patterns) based on *correlation length*, and, therefore, "what you can take with you and what you must leave behind as you gradually move upscale from a microscopic description to a macroscopic one" (Davies, 1989). A macroscopic configuration actually represents the step-wise repeats of microscopic configurations, a relationship exemplified by well-formed turbulence and its eddies, respectively.

There is no doubt that the nervous system has evolved to deal with extra-personal space and the non-self environment by generating the most appropriate behavior or response. The brain accomplishes these highly complex tasks by creating effective replicas or environmental maps of the world with which it interacts. Should the brain follow the basic principle of *re-normalization*, an effective replica of the world can be easily constructed in a scale where brain neuronal networks can effectively handle all the essential information for generating a timely and appropriate behavior or response. The presented model of the brain is highly consistent with such an "ultimate" machine.

Re-Normalization and Multiple Resolution Representation

It is well known that identical feature/information representations appear repeatedly in lower degrees of resolution in the brain (Kandel et al., 1991, Arbib, 1995). This apparent redundancy is a key characteristic of the brain and distinguishes it from modern engineering. The essentials of this redundancy are readily explained by the presented model and the *re-normalization* concept described above.

Let's consider visual information processing as example. The human retina contains over 100 million neurons comprising at least 30 different cell types utilizing 20 different neurotransmitters (functionality). In a highly simplified view, a single instant parallel two-dimensional set of visual information can be regarded to be handled by 1 million neurons or approximately a 1024 x 1024 matrix. Supposing the brain indeed uses the re-normalization schema in the visual cortex, six consecutive repetitions of a three to one reduction of the matrix size by hexagonal decimation (see Appendix) will reduce the matrix size to less than 32 x 32. This matrix size is highly compatible with a group of 1000 neurons, the approximate size with which a single feature/information is believed to be processed in the cortex.

The re-normalization process described above is generally referred to as *coarse graining*. Each re-normalization process, such as the decimation process, provides the identical features in lower resolution, the reduction rate of which is determined by the *correlation length* (Davies, 1989). Each re-normalization step produces an effective replica of the feature/information in a smaller matrix (lower spatial resolution). The successive repetition of this re-normalization process eventually yields a replica which is small enough to be handled as *principal quantum* of the brain (see below). The series of compression processes require the identical feature/information to re-appear in successively lower resolutions.

The universal rule of the *re-normalization* schema represented by c*oarse-graining* is not only highly consistent with the phenomenology of actual brain processing, but also provides the basic essential reason for having multiple representations.

Two Dimensional Hexagonal Matrix and "Principal Quantum"

In general life, a two-dimensional matrix is often treated as a square matrix primarily due to its simplicity. Theoretically, however, a hexagonal shaped matrix is ideal (Rosenfeld & Kak, 1976). As illustrated by the *Marangoni convection* cells mentioned before, many macroscopic phenomena often encountered in nature provide observable examples of hexagonal matrices. In the case of lattice-gas cellular automata in fluid mechanics, it is known that in order to obtain the Navier-Stocks equation exactly, the lattice has to possess sufficient symmetry to guarantee isotropy of the fourth order tensor. It is well known that the hexagonal Frish-Hasslacher-Pomeau (FHP) lattice in two-dimension meets this condition (Doolen, 1991). The two-dimensional hexagonal matrix appears in various structures of the brain as well. The primary visual cortex and the cerebellum represent typical examples (Eccles & Szentágothai, 1967, Lund et al., 1993).

A two-dimensional hexagonal matrix, which possesses a totally isotropic degree of freedom of six, appears to be the principal matrix in nature when *self-organization* plays a main role. This type of matrix appears to be applicable to brain organization, especially in information processing. The ripple model of auditory processing provides strong support to the notion that feature/information in the brain is processed and/or travels in a fashion similar to the visual modality (Shamma et al., 1993, Arbib 1995). As discussed previously, a hexagonal matrix equivalent to approximately a 32 x 32 square matrix is a good candidate for archived visual information created by successive re-normalization processes. In order to be able to accomplish multi-modality comparison and processing, it is efficient for the brain to use a *standard quantum* size to represent identical or related feature/information for each of the modalities. In this context, it is highly conceivable that a hexagonal matrix equivalent to approximately a 32 x 32 square matrix may indeed represent the *principal quantum* of feature/information representation (engram) in the brain.

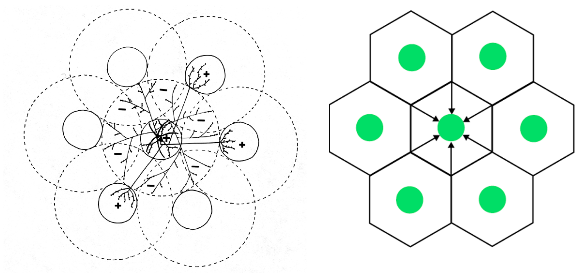

Figure 10

Schematic presentation of the primary visual cortex (left: redrawn from Lund et al., 1993) and equivalent hexagonal matrix (right). Arrows indicate "decimation" (see Appendix).

Specific Meaning of Columnar Organization

One of the most significant corollaries of this hypothesis is that the model provides specific meaning to the well recognized columnar organization of the cortex, one of the essential features of the brain (Kandel et al., 1991). The self-organized brain shape based on free convection ensures that flow is always perpendicular to the surface of the brain within the cortical columns. An entropy-vortex wave always travels along with the initial flow and, hence, within the identical column. A *lattice-gas shell* which is self-organized into *Marangoni convection* cells creates the first step of information processing in the form of a two-dimensional hexagonal cellular automata system, and is highly consistent with columnar organization as well. The ELDER system connects the lattice-gas shell to the neuronal network shell, which in turn creates a cascade of multi-step processing in the fashion of stacked two-dimensional hexagonal layer networks. The three-dimensional realization of this stacked multi-step two-dimensional processing is indeed again columnar organization.

A Tangible Definition of Consciousness

Another essential corollary of the hypothesis is a tangible definition of consciousness and a plausible answer to the long time mystery in anesthesia: Why anesthetic effect fades out when the subject is placed in an environment with higher atmospheric pressure. The Vortex Model can readily address these issues.

Steady flow, the basis of an entropy-vortex wave, and the establishment of self-organized *Marangoni hexagonal convection cells* within the lattice-gas shell of the brain require a certain thermodynamic steady state or homeostasis. The thermal gradients required to produce a convective force are dependent on the presence of the appropriate heated solid body core. It is highly conceivable that establishment of the required thermodynamics, and hence, establishment of steady state cortical activities through the ELDER system makes the brain *conscious*.

All major anesthetic agents, including alcohol, are chemical compounds with a low boiling point. By accepting the presented model, it becomes highly plausible that the basic mechanism of anesthetic agents is their effects on the kinetic viscosity (Reynold's number) of the fluid (gas) of the steady flow. The addition of a relatively heavy fluid (gas) such as anesthetic agents produces alteration in the kinetics of the steady flow and, hence, affects self-organization of the lattice-gas shell. At higher atmospheric pressure, the boiling point of these agents is reduced resulting in diminution of their anaesthetic effect. At lower atmospheric pressure, the boiling point of these agents is facilitated resulting in greater effect, explaining the well known phenomenon of increased alcohol effect in airplanes.

Logical Power Supply

Consider logical processing devices such as digital computers. In addition to input and output current, there is always a power supply for each discrete logical circuit. The voltage of this power supply is in principle identical for all the discrete circuits of the system, ensuring correct processing.

Biological systems depend on a biological power supply and have evolved to utilize as supply compounds such as high-energy phosphates (HEP) for cellular survival and function. Therefore, it is intuitively accepted that neuronal networks also utilize HEP as energy source. This is obviously true for certain biological aspects of neurons and other cellular components of the brain. However, it is actually doubtful that the brain utilizes the biological power supply system, needed for information processing as well, as *logical power supply*.

Cortical neurons vary considerably in size and shape. It is very unlikely, therefore, that all neurons possess identical HEP levels all the time. In addition to being a biological organ, the brain is also a highly sophisticated device involved in information processing. It is quite conceivable, therefore, that the brain utilizes two different kinds of power supplies, namely, a *biological* power supply and a *logical* power supply.

The presented model provides for a steady *logical power supply* of identical magnitude to all cortical areas. The steady flow established for the resting conscious state of the cortex produces spontaneous, non-specific, diffuse "steady state" activities of cortical neurons through activation of the ELDER system. Electrically transmitted neuronal inputs are first converted into non-electrical entropy-vortex waves which travel along the cortical columns to reach the lattice-gas shell. There, information is converted back to electrical information through processes within the lattice-gas shell and the ELDER system. The initial cortical output is effectively calibrated by the *logical power supply*, ensuring proper and accurate processing downstream in the neuronal networks.

Endogenous Source of Initiation

A non-electrical activation system of the lattice-gas shell and its conversion into electrical activation through the ELDER system together with spontaneous non-specific diffuse steady state activities of the *conscious* brain allow for activation of neuronal networks without necessity of any sensory input. The system ensures the capability of purely endogenous initiation of electrical information processing from virtually any part of the cortex. It provides another highly plausible explanation for the long-time unanswered question: how the brain initiates endogenous thinking without any sensory input.

Higher Degree of Freedom and Creation

The human brain is capable of creating totally novel abstractive features. It is difficult to conceive that such brain activities can be operated based on a totally deterministic system. It is quite unlikely that brain function such as abstract thinking and/or creativity can be supported by a totally discrete network system of neuronal connectivity regardless of its level of complexity. If the brain requires a high degree of freedom for function, it is likely that it would need to have a system which possesses a high degree of freedom. The Vortex Model provides a much higher degree of freedom in information processing by virtue of cellular automata. Synaptic alteration and, hence, changes in neuronal connectivity (or transmission efficacy) constitute the secondary system for information processing. The former allows for creation, while the latter, execution and memory.

Potentials

Solitons for Binding?

In 1960's, Hama and colleagues introduced a series of publications regarding deformation of a single, strong vortex filament under its self-induced velocity, idealized using an asymptotic analysis (Hama, 1962, 1988). The theory is now generally referred to as localized-induction approximation (LIA). In spite of various shortcomings, LIA solutions have provided useful clues to the large-scale behavior of a concentrated vortex. It is apparent that under well-controlled, small-scale conditions, as in the case of entropy-vortex waves described above, critical concerns for the application of LIA, such as deformation of the vortex core, can actually be treated as negligible. Additionally, the steady flow compartment could be made to meet the boundary conditions required for application of appropriate asymptotic analysis. It is highly plausible, therefore, that one of the behaviors of a vortex in the entropy-vortex waves described in the hypothesis can indeed be represented by LIA.

A significant outcome of LIA type vortex dynamics is the fact that the dynamics of a vortex filament represented by LIA can be transformed into a non-linear Schrödinger equation (NLS) and, hence, supports solitons (Hasimoto, 1972) (see Appendix). The transformation implies that the entropy-vortex waves of the hypothesis can have physical significance in producing certain specific turbulence patterns associated with specific input perturbation, namely, that compatible with solitons, in addition to the perturbation for local input of the *lattice gas shell*.

One of the long-debated subjects in neuroscience is the so-called "binding" problem. Consider a free falling red apple as example. It is well known that each "component" of the entire phenomenon, namely, free falling (motion), red (color), and apple (shape) are processed at different sites in the brain. Nevertheless, one perceives it as a single phenomenon. Therefore, the brain should have some mechanisms to *bind* these apparently independently processed pieces of information. Unfortunately, there has been no definite system identified in the brain that performs this binding process (*binding problem*).

Solitons have the potential to solve the long-range binding problems. The well-known unique characteristics of solitons are: (1) solitons travel long distances without significant dispersion; and (2) solitons continue to travel with virtually identical shape and direction even after they collide. Should entropy-vortex waves introduce solitons in addition to input turbulence to the lattice-gas shell, information processing and long-range binding can be simultaneously taken care of by the identical entropy-vortex waves. The neuronal networks of the brain often utilize collision or coincidental arrival of impulses for learning (synaptic transmission efficacy changes). The cortex may indeed utilize similar strategies for long-range binding, namely, one impulse from the conventional neuronal network and another from solitons travelling in the lattice-gas shell.

Requisiteness of Phylogeny

One of the breath-holding beauties of Mother Nature is phylogeny. With painstaking effort, in time, Mother Nature has created, revised, refined, and perfected structure for the desired function. Development of the frontal lobe and hemispheric specialization represent two unique results of Mother Nature's efforts in creating the ultimate brain. As with any phenomenology in nature, development of the frontal lobe and hemispheric specialization should have a specific essential (or unavoidable) reason.

From the phylogenetic standpoint, reason is not synonymous with purpose or goal. Reason should be a natural occurrence, which by chance produced beneficial effects for the organism. The significant occurrence in the evolution of Homo sapiens compared to the other mammals is our *erect posture*. Any other human feature should represent the result rather than cause of phylogenetic development of the human brain. Can we explain the development of the frontal lobe and hemispheric specialization by the *erect posture*? The answer is yes, providing one accepts the following presented hypothesis.

Given that brain development followed the *self-organization* rule based on free convection, the *erect posture* results in the backward rotation of the axis of the brain[13], generating additional growing space in the frontal area (α in Figure 11). Development of the brain in this functionally "undefined" area[14] may indeed have provided the necessary "degree of freedom" in developing abstractive functions such as working memory and selective attention.

The principal feature of the presented hypothesis is the *vortex*, the traveling wave which possesses vorticity. As seen in the example of a gyroscope, a traveling vortex subjected to a force angled to the surface of vorticity will be affected by torque. Should the direction of vorticity be identical in both hemispheres, torque introduced by the earth's gravitational force will affect the kinetics of the vortex and introduce minute differences in the energy distribution between the right and left hemispheres. Such effects introduce asymmetry within the brain. This provides the essential reason for asymmetry in the brain, a structure which otherwise would have been totally symmetric. Non-human primates are known to have significant anatomical asymmetry of the brain. This observation supports the notion that asymmetry of the brain appears prior to the appearance of hemispheric specialization.

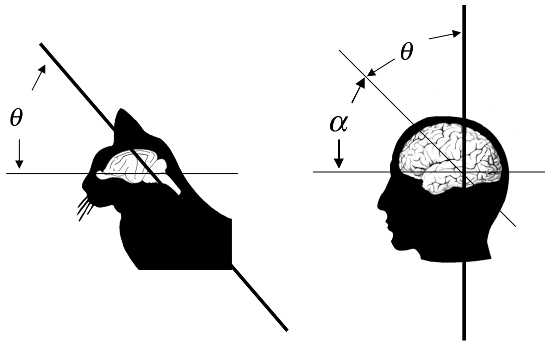

Figure 11

With the development of functional asymmetries in motion (handedness) and audition and vocalization (language) in the human, this pre-existing asymmetry became the basis of the formation of hemispheric specialization. The erect position alters the physical relationship of vortex and gravitational force in certain areas of the brain more than others. The highest effect occurs in the regions located within the axis perpendicular to the earth's surface which passes the center of the rotation and coincids with the areas subserving the primary motor and auditory cortices.

Finale: Mother Nature's Constitution

The hypothesis presented links together virtually all neurobiologic phenomenology, many

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[13] Clockwise when one views the brain from the left hemisphere.

[14] The sensory and motor areas have been securely defined without the frontal lobe. Therefore, the appearance of additional brain tissue in the frontal lobe can be treated as "luxury", which can be dedicated to other "advanced" functions.

of which thus far unexplained. In this context, the hypothesis represents a grand unification theory of how the brain works. The most important features of the hypothesis are that it is based on the universal concept of complex systems and allows for anatomical realization. There is already substantial evidence to support the hypothesis. The unchallenged part of the hypothesis is fully testable.

Nature represents a highly complex system. The brain is no exception. Accumulating scientific knowledge has slowly disclosed the basic principles to deal with complex, non-linear systems (Lam, 1997). The critical point phenomenon and phase transition provides theoretical as well as practical applications over a surprisingly broad range of science and engineering. Microscopic behavior actually defines macroscopic behavior through the universality and re-organization principles (Davies, 1989). Self-organization phenomena based on the principal rules result in structural realization widely observed in nature in areas as diverse as geology and biology.

Just as Shannon's entropy revolutionized information science (Cover & Thomas, 1991), the concepts originally derived from thermal physics, as illustrated by the Bolzmann machine, now play essential roles in computational neuroscience (Arbib, 1995). Guided by the advancements in modern physics, scientists now clearly realize that all the phenomenology that has been classified into different fields of science actually represent outcomes from identical principal rules of the universe.

Twenty first century science must by necessity be highly multi-disciplinary, an approach that has been shown to be successful in the field of non-linear physics (Lam, 1997). Unfortunately, communication difficulties have by and large prevented effective exchange among scientists across substantially different disciplines. This is especially true between biologists and physicists. I hope (and believe) that, by introducing the current hypothesis, the distance among scientists who want to deal with the brain, regardless of their discipline, has been substantially shortened. We now possess an identical language based on the principal rules of the universe: *Mother Nature's Constitution.*

Acknowledgement

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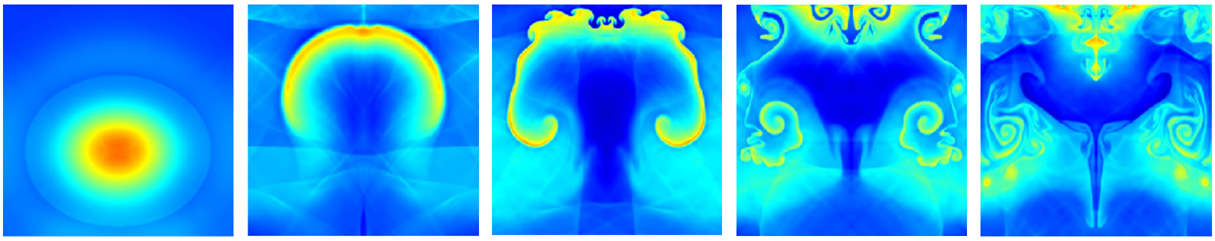
Appendix

- Brain and Self-organization -

Three-dimensional simulation of free convection has been performed utilizing a SGI origin 2000 64 CPU system. Governing equations in Eulerian form are given below. Subroutine FORTRAN codes of PPM schema (Woodward, 1982, Colella & Woodward, 1984) was obtained from http://wonka.physics.ncsu.edu/pub/VH-1/. The representative examples of two-dimensional "slice" images of consecutive steps of the simulation were sampled and showed below. Details are reported elsewhere (Nakada & Suzuki, 2000).



$$\frac{\partial}{\partial t}\rho + \nabla\cdot(\rho\mathbf{v}) = 0$$

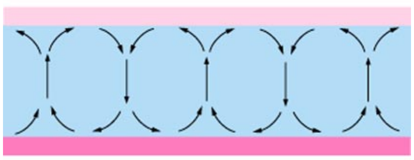
$$\frac{\partial}{\partial t}(\rho\mathbf{v}) + \nabla\cdot(\rho\mathbf{v})\mathbf{v} + \nabla p = \mathbf{F}$$

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \nabla\cdot(\rho\varepsilon\mathbf{v}) + \nabla(p\mathbf{v}) = G + \rho\mathbf{v}\cdot\mathbf{F}$$

$$\textit{where} \quad \varepsilon = \frac{\mathbf{v}\cdot\mathbf{v}}{2} + \frac{(\gamma-1)^{-1}p}{\rho}$$

- Bénard convection-

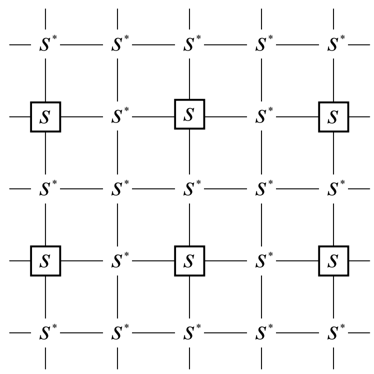
Conventional Bénard convection is described for a fluid layer which lies between two parallel plates. The temperature of the lower plate is higher than that of the higher plate. The fluid undergoes a "peculiar" convection pattern forming multiple blocks (cells).



- Decimation -

One of the simplest examples of coarse-graining is the method of *decimation* (Davies, 1989). Coarse graining by decimation effectively eliminates certain fractions of spins on the lattice producing a new system (coarse-graining) which still contains the long-distance physics of the original system (fine-graining).

The process can be illustrated as follows. The spins of the Ising lattice are divided into two sets: {s} and {s*} as shown. The spin {s} forms a lattice of spacing 2. The appropriate energy function H for s can be defined by performing an average over all the possible arrangements of the s* spins with energy function of H^*:



$$\exp(-H) = \Sigma_{\{S^*\}} \exp(-H^*).$$

Here, a new set of the spin {s} describes the original system by "coarse" lattice.

- Hasimoto Soliton -

Betchov's intrinsic equations are given as:

$$\frac{\partial \kappa}{\partial \theta} + \frac{\partial(\kappa\tau)}{\partial s} = -\frac{\partial \kappa}{\partial s}\tau$$

$$\frac{\partial \tau}{\partial \theta} - \frac{\partial}{\partial s}\left(\frac{1}{\kappa}\frac{\partial^2 \kappa}{\partial s^2} - \tau^2 + \frac{1}{2}\kappa^2\right) = 0$$

where κ represents curvature, τ, torsion, θ, time variable, and s, arclength, respectively (Anderson & Greengard, 1991, Saffman, 1992).

As Hasimoto has shown, if a "wave function" is defined as:

$$\psi(s,\theta) = \kappa(s,\theta)\exp\{i\int^s \tau(s,\theta)ds\},$$

the equations can be elegantly transferred into a non-linear Schrödinger (NLS) equation of:

$$i\frac{\partial \psi}{\partial \theta} + \frac{\partial^2 \psi}{\partial s^2} + \frac{1}{2}|\psi|^2\psi\,,$$

which possesses soliton solutions (Ablowitz & Harvey, 1981, Remoissenet, 1996).