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Thoughts about Thinking: Cognition According to the Second Law of Thermodynamics

Saara Varpula[1], Arto Annila[1,2,3,*] and Charles Beck[4,*]

[1]Department of Physics, [2]Institute of Biotechnology and [3]Department of Biosciences, FI-00014 University of Helsinki, Finland
[4]Department of Psychology, University of Alberta, Edmonton, Canada

Abstract

A holistic account of the human brain is provided by the Second Law of Thermodynamics. According to this universal precept, the central nervous system is governed by the quest to consume free energy in the least possible time. The brain is like any other system of nature that has evolved over eons and continues to develop over an individual's life time. This physical portrayal is singularly appropriate because power-law characteristics as well as oscillatory and at times unpredictable functioning are not exclusive attributes of the brain but are found in other systems throughout nature. The neural network comprises pathways for signal propagation just as other natural systems have pathways for the transmission of energy in various forms. These universalities support the view of the evolution and development of the human brain as a natural thermodynamic process. In a like manner perception, sensation and learning as well as the processes of memory, emotions and consciousness can be regarded as natural expressions of the neural network under the suzerainty of the Second Law. The outcomes of cognitive processes, like other natural processes, are non-deterministic because the interactive effects of flows of energy as signals with differences in energy as their driving forces cannot be separated from each other. This naturalistic framework also provides insight into mental disorders and cognitive defects.

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*arto.annila@helsinki.fi
*cbeck@ualberta.ca

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1. Introduction

The human brain, despite its complexity, is no different in its operational principle from any other system in nature. This view may seem to diminish the uniqueness of the central nervous system, and may surprise some since it implies that all natural systems comply with the same universal imperative. This supreme law of nature is no mystery, but is known by many names, most often as the second law of thermodynamics [1] and the principle of least action [2]. In addition, the maximum power principle [3], and most notably evolution by natural selection [4] can be recognized as accounts of the probable process for the least-time consumption of free energy [5,6].

The irrevocable least-time consumption of free energy yields certain characteristics that are found throughout nature. Namely, sigmoid growth and decline as well as skewed, nearly log-normal distributions are ubiquitous [7,8,9,10]. In addition oscillatory, chaotic and non-deterministic behavior [11,12,13] as well as power-law scaling and branching are typical qualities of natural systems [14,15,16,17,18,19]. These universalities emerge from the quest for the least-time free energy consumption [20,21]. Significantly, these scale-independent attributes of natural networks have also been found in studies involving recordings and images of brain [22,23,24, 25,26,27,28,29].

Considering the irrefutable imperative to consume free energy in the least time, it is hardly a surprise that the human brain also exhibits this universal characteristic. Indeed the brain has been examined from this perspective earlier [30,31,32]. However, our intention is not to propose a mathematical model of neural networks, but to examine the implications of this viewpoint for how we think about the brain's evolution and development as well as for the functional processes perception, sensation, memory, learning, sleep, emotions and consciousness. Undoubtedly this short survey may appear to be superficial when subsuming specific details into the general terms of physics [33]. However, the formalism when derived from statistical physics of open systems, complies with conservation of quanta to a precision of a single quantum [6,34]. Accordingly, our aim is to provide an inspiring yet an evidenced based account of cognition through the application of the universal law of nature. The scale-independent natural principle when given as an equation of evolution [6,21,35], allows us describe the human brain in the same way as we describe other systems in nature. When general concepts are employed, specific mechanisms of any system will be secondary to the governing objective of all systems to consume free energy in the least time.

2. Natural processes

Life at each and every level of the natural hierarchy manifests itself as an interaction of thermodynamic processes [36,37]. Thus, according to the scale-free naturalistic tenet, the human brain, like any other system, has evolved over the eons just as it develops over an individual's life time to attain balance, known as the free-energy minimum, with respect to its surroundings. In other words the physical portrayal makes no principal distinction between evolutionary and developmental processes or gaining experience by trial and error, but regards all processes as being ultimately guided by the same universal imperative of least-time free energy consumption. Only their means and mechanisms differ.

This basic perspective means that any change in the brain, whether inherited genetically or induced as epigenetic or imposed as neuronal network changes, will be considered advantageous when it contributes to the consumption of free energy. Identifying this primal force will clarify the significance of inherited and acquired changes in shaping the brain. Whereas natural selection is the proximate cause of neural and behavioral adaptations, consumption of free energy, the essence of the 2nd Law of Thermodynamics, is the ultimate cause.

According to the variational principle, the flows of energy themselves will search for the paths of transduction and naturally select those that consume free energy in the least time [38]. This gradient in energy is the natural bias of evolution and development. It will manifest itself, e.g., when a neuron acts as a target for neuro-trophic factors [39] and when a dendritic process reaches another neuron to make new synapse. Likewise, a bacterium will chemotax along nutrient gradients and a human individual will seek more resources, e.g., by acquiring an education and finding better work. Similarly a society will direct its activities, such as building infrastructure, expecting increased returns, i.e., access to free energy. So, the natural bias implies also intelligence, when the adaptation is understood as a relational attribute of the system's ability to devour free energy from its contemporary surroundings.

It is noteworthy that the general conclusion about the preferred directions of natural processes does not depend on a particular choice of how a system is defined. For example, a brain be enriched when its host body has evolved in its abilities to extract more assets from its surroundings, e.g., by obtaining more nutrients. Conversely, when the brain has developed cognitive means to acquire more resources, e.g., by learning faster, so the body will find itself in more profitable sur-roundings. In other words there is no need for mind-body dualism, since systems are within systems and everything depends on everything else [40]. The proximate mechanisms differ but the processes do not.

Although the common driving force of evolution and development is easy to state in thermodynamic terms, mathematical analysis of the evolutionary equation of motion will reveal why it is impossible to compute trajectories of specific natural processes [41,42]. Namely, when the flows of energy, such as electric currents, and the differences of energy, such as voltages, as their driving forces cannot be separated from each other, the precise evolutionary and developmental paths cannot be predicted by integrating them from an initial state to a final state. It is a mere consequence of conservation of quanta that an evolutionary step, just as a developmental step, will alter both the system and its surroundings, i.e., boundary conditions keep changing [34,43]. Due to this intrinsic interdependence between the system and its surroundings evolution itself changes its settings, i.e., the energy landscape. Therefore the natural processes are path-dependent and remain inherently intractable. Thus there is a profound reason why the brain appears to operate as a non-algorithmic processor. Parenthetically it should be emphasized that non-determinism does not stem from the complexity of a system as such nor from indeterminism ascribed to quantum systems.

3. Sensations are energy flows

The holistic account of nature describes the human brain like any system in interaction with its surrounding systems via flows of energy. Accordingly, perception can be regarded as a physical process of energy transduction. Flows of energy from the surroundings enter as visual, auditory, vestibular and pain sensations. These forces in various physical forms are transformed to neural signals. Subsequently the signals project toward the central nervous system along paths provided by neural connections. By contrast, a subject will fail to notice an environmental stimulus if there are no means to sense it or to conduct it further. Moreover, he/she will struggle to make sense out of his/her sensations when a particular physical representation of information as a flow of energy [44] enters the central nervous system but finds no established template or schema for recognition. Then the individual tries to establish new pathways which would allow him/her to rationalize the perception by consuming the free energy associated with the physical representation of the signal.

Curiously though, when the subject has already established effective paths to cope with a particular stimulus, he/she will often fail to make a distinction between it and another, very similar stimulus. Physically speaking, nascent sensitivity, e.g., for learning languages relates to an uninitiated neural network which is an unmolded energy landscape [45,46]. Later, when the connections have been made and strengthened, the flows tend to follow the established paths. Thereafter investments in opening even more effective lines of reasoning are high in comparison to the expected returns measured in terms of increased energy transduction that a revised behavior would ultimately bring about. Likewise a river prefers to run in its normal bed, but during a flood, water may find a new more voluminous channel. Afterward only old cut-off meanders will indicate the original course of the river.

The brain of a new born contains the potential to adapt to diverse circumstances. Likewise, stems cells are pluripotent, just as ancestral species were multipotent, in developing diverse functions in response to surrounding energy densities. Later, when cells have specialized for a particular task, just as many contemporary species have refined their means of energy transduction to a specific setting, these systems can no longer readily readjust their extensive and perfected energy transduction machinery to draw effectively from the markedly changed surroundings. Accordingly, a newborn will often find ways to circumvent a defect by neural rerouting or by allocating its nascent neural network to other functions than those lost, whereas an adult suffers for a long time from lesions, and phantom sensations tend to persist in the adult's structured brain for some time. Nondeterministic systems are robust.

When the brain is isolated for a long time from sensory stimuli, no energetic bias will be provided by the surroundings to impose and maintain specific neural structures that direct the dispersal of energy. The ensuing idleness is no blackout but intrinsic activity manifests itself, e.g., as hallucinations and random processes [47,48]. When the energetic bias is absent, but metabolic propellant has to be consumed in one way or another, the neural network becomes incoherent. By analogy, no river will run through completely flat terrain but loses its track and disperses and eventually dissipates via evaporation and percolation. These concepts about the organizing principle of brain are by no means new. The principle of least action has been exploited over iterations of intracellular dynamics, synaptic dynamics and synaptic regression [49]. Here we wish to emphasize the principle in its physical form by exemplifying the forces as concrete resources and the flows of energy as tangible currents.

4. An energy flow revives a trace of memory

According to the thermodynamic principle the neural network is an energy transduction system like any other natural system (Fig. 1). Activated neural paths for energy dispersal constitute memory. A recollection is embodied in a flow of energy that will funnel as an action potential along established neural lines. These transduction paths were formed when an experience, also encoded in some form of energy, was recorded. The signals searched for and eventually opened a new path for the least-time energy dispersal. Thus the neural network is the register of remembrance that can be retrieved, consolidated and re-cognized, when the particular path is flushed again with a flow of energy. In other words, a memory persists in its pattern as a specific flow of energy just as an animal thrives in its ecological niche by consuming energy in a variety of nutrients. Conversely a memory will fade when not renewed. Likewise a river bed will close with vegetation or debris when not flushed once in a while.

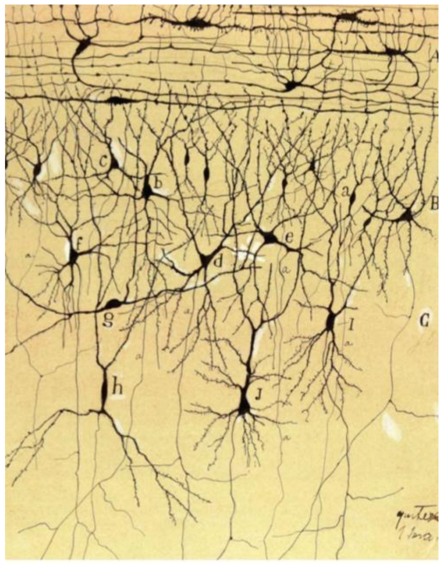

Fig. 1. According to the principle of least action a neural network is as an energy transduction system that has evolved and developed to conduct and disperse signals in the quest to consume free energy in the least time. (Capas 1a y 2a de la corteza olfativa de la circunvolución del hipocampo del niño, n. 1901 © Herederos de Ramón y Cajal)

Our memory is not a reliable source of recollection, as is apparent from criminal investigations. A memory trace may be subject to active reconsolidation or even driven by unconsciousness incentives. So we remember what we like to remember and tend to forget what we wish to forget. The natural bias of subjective selection directs memory along the path of least resistance. The inherent intractability of natural processes will manifest itself when something unexpected crosses one's mind. Physically speaking, when a flow of energy spills over from one path of a register to another, the two pathways will connect with each other. Likewise, a molecular orbital force will bind atoms to a molecule with emergent properties [50]. Also sporadic gene shuffling may at times link formerly unrelated fragments of genetic directories to yield a new functionality. From this naturalistic perspective the huge capacity of the human brain to make neural connections provides potential for far-reaching diversification to facilitate unprecedented adaptation to diverse surroundings. The neural paths can extend and branch out, e.g., to register distinct memories as well as to differentiate between subtle sensory recordings and to tune motor functions for fine maneuvers.

Considering the huge capacity of human central nervous system for diversification, many circuits are bound to have only small energetic biases relative to each other. Thus, even a small tilt or offset in the energy landscape may suffice to obscure the distinction between delusion and reality. Likewise, when a river branches into many competing estuaries, even a slight tilt of terrain at the delta will redirect the flows.

5. A bias in energy is a lead for learning

Physics envisages cognitive processes as natural processes, so a neural network will adjust to its surroundings by consuming energy differences, i.e., net forces. Stimulation is a vital supply of energy for a neuron. Synapses will degrade when deprived of fueling action potentials. For instance motor skills will decline without exercising [51]. This holistic view of the brain, although expressed using the general concepts of energy, parallels the biological assertion that learning is the way for an organism to adapt to its surroundings. Reinforcers, e.g., all sorts of carrots and sticks, are ultimately encoded in terms of free energy that will be consumed during learning processes. Conversely, under inconsistent circumstances the reinforcers for learning, i.e., the energetic biases will be fluctuating, hence no firm paths can be established and therefore behavior will be unpredictable. Likewise, an ecosystem when being repeatedly perturbed by changing conditions, will not develop complex energy transduction machinery, i.e., flora and fauna. The disturbed system cannot expand from its current locus but its populations rise and fall repeatedly [52].

It is well-known that it is more effortful to alter one's habitual thoughts than to adopt a new notion in the first place. To revise an erroneous impression or an unfounded fear will require not only that a new way of thinking will be physically developed and the old one abandoned but also at times that flows of energy as signals along the old, flawed lines of thought will be inhibited [53,54]. Likewise, to reroute traffic on a new highway, the old familiar road will have to be blocked for it to be discarded. When changing one's mind, flows of energy will reroute. Thus it depends on the subject's neural network characteristics that have been acquired and established in the past, how or whether a new experience will be learned. Plasticity, which is a general characteristic of natural networks [55], is obviously vital when one is recovering from lesions.

The physical portrayal of brain as an energy transduction system clarifies why a particular piece of information will be appreciated by one individual but not by another. The individual who has obtained a ability, e.g., genetically or by experience, to use the free energy associated with information can take advantage of the new information whereas the same piece of data may be problematic for another, who has no means to access and consume the source of free energy. The subjective characteristics of cognition are encoded in the paths of individually distinct neural networks, and are expressed in the disparate ways that the same information is interpreted by different persons. In the same way, a metabolic system of a species has been adapted to a preferred diet and struggles to combust energy in other forms.

The non-deterministic character of cognitive processes follows from the non-holonomic processes not from some indeterminism in coherence transfer between a source and a receiver [56]. There is no deterministic algorithm of cognition when the flows of energy as signals and their driving forces as differences of energy depend on each other. When a flow along a neural branch affects all other flows that are consuming the same source of free energy, there is no way to compute behavior. Moreover, the flow itself will affect its own conduction, e.g., by strengthening specific synapses a subsequent flow will also be affected. Likewise, when a river branches at its estuary, a flow along one channel will affect flows along others. Moreover the river itself will by the act of flowing erode its landscape and affect its own flow. Thus, the non-deterministic nature of the neural network does not stem from brain's complexity as such but appears already in the problem of three bodies [57] and other complex problems with two or more degrees of freedom [58]. The non-computable character is inherent to adaptive systems. The individual, when provided with free energy, i.e., with motivation, and mechanisms of learning, may consciously or unconsciously re-establish his/her lines of reasoning.

6. Sleep serves to restore the maximum entropy balance

The scale-free formulation of natural processes using general terms of energy allows us to also dissect perplexing phenomena such as sleep by identifying advantages of similar processes found in other systems.

When fast asleep, anabolic assets will accumulate for wide-awake peak activity. Likewise, social systems will pool resources for subsequent coordinated actions. Not only the brain but also ecosystems and economic systems with powerful mechanisms of energy transduction will be readily driven in a boom-bust cycle when free energy is consumed faster than it is replenished from surroundings [59]. Considering the brain's high proportion of the body's power consumption, the organ is rightfully regarded as the individual's most effective mechanism in facilitating free energy consumption.

In general, periodicity is a common mode of operation to orchestrate operations. For instance, work in factories and offices is coordinated with daily rhythm. Also, sleep cycles with distinct phases indicate synchronized activity. Following the principles of physics, low-frequency cycles of deep sleep will integrate large portions of the brain for coherent activity whereas high-frequency oscillations will structure small fractions to execute specific tasks. It follows that deep sleep serves to restore the balanced distribution of maximum entropy by restructuring and synchronizing large neural networks that were shattered by high-frequency processes of cognition when awake. The repeated sleep cycles that develop during the night into a full choreography, imply that the restorative revision of the neural network is an iterative process. Iteration is a typical mode of operation for the non-deterministic natural processes that direct toward a free energy minimum that cannot be algorithmically determined beforehand. Moreover, from this physical perspective it seems understandable that adults display a spectrum of frequencies that are on the average higher than children because adults have already accumulated a finer diversification of the neural network to be fed by signals [60].

Apparently, active sleep serves to prepare the individual and perfect his/her processes for various detailed situations when awake. Dreams may seem real enough to invoke responses but the paralyzed body is protected during rehearsals. Moreover, when cognitively active self-surveillance is suppressed, there is more freedom for exploration and the opening of new pathways of energy transduction across the mind. This unrestrained mode of operation may be particularly important for ingenuity or for creative endeavors. Also social systems afford seemingly irrational acts, such as parties and celebrations, which typically generate unexpected contacts and opportunities, some of which may provide a new means to consume free energy. The significance of the arts as facilitators of new ideas is universally recognized. The arts promote also social gatherings across cultures. Increased social cohesion contributes to increased free energy consumption [61]. Here, as anywhere else, without variation there is no opportunity for natural selection.

Energy transduction is a characteristic of any process and in this case is critical in maintaining a healthy brain. During sleep and wakefulness, neural oscillations at various frequencies, amplitudes and phases are driving distinct functions. In the same way periodic patterns, e.g., chemical bond vibrations, cellular cycles, circadian and annual rhythms associate with specific activities at various levels of the natural hierarchy. Conversely, when no energy is flowing along the neural paths, the brain is "dead" although its metabolic pathways are still conducting. Obviously in the brain, as in any other hierarchical system, various functional levels are connected to each other, e.g., gene-expression and metabolic activity relate specifically with activities during wakefulness and sleep as well as during sleep deprivation [62].

In general, maintenance is mandatory for all living systems, but apparently a subtle balance between secure stagnation and risky progress is typical of highly evolved systems. The condition of our brain is a tightly but not completely controlled homeostasis, just as correctness of our genome is monitored by high-fidelity but not perfect proofreading. In accord with findings [63], we expect even small imbalances or variations in flux of energy in terms of transmitters or metabolites through a clocked circuitry to manifest itself as uni- and bipolar disorders. Mode-locking and mode-switching are also familiar phenomena in mechanical and electronic systems that are driven by an external bias. Chaotic behavior is triggered by sudden changes not only in brain but also in many other systems, e.g., in lasers [64] cellular automata [65] and weather. Episodic abnormal neuronal activity causing seizures is paralleled, e.g., by avalanche breakdowns in semiconductor circuits [66]. Similarly, the balance between sleep and wakefulness is subtle [67]. The quality of sleep obviously affects daytime activities, and conversely the quality of activities when awake influence sleep.

7. The notion of self

Emergence of identities is a natural outcome of energy dispersal since indistinguishable entities are by definition devoid of mutual differences in energy to be consumed. The identity of indiscernibles implies that the self develops to distinguish the being from its surroundings. Identity is vital. A person develops his/her personality, i.e., ways of behaving and thinking, to live in diverse circumstances. Apparently under certain conditions, presumably resulting from conflicting demands, the process toward an integrated personality cannot proceed coherently but will bifurcate and yield a split character [68]. Similarly, when the body fails to make a distinction between itself and surroundings, it will become incompatible with itself e.g., expressed as autoimmune diseases.

Awareness of one's own activities [69], just as is the case with other processes, serves to consume free energy, e.g., by coordinating actions and guiding planned actions. Accordingly, consciousness is primarily considered to be a mechanism for the individual system to boost its energy transduction. Likewise, a nation monitors its own activities, e.g., by acquiring statistics and by polling its status, as well as by following foreign affairs to act optimally. The degree of consciousness increases along with increasing integration. High-frequency communication within the system supports the sense of being one, the self. However, consciousness will emerge without an abrupt onset while the web of energy transduction paths is developing. Hierarchical development of the means of transduction parallels the integration process [70].

Yet certain events may require such rapid responses that the individual will attain the integrated level of consciousness only later. Emotions appear as meaningful mechanisms to invoke all-embracing activity integrating system-wide neural and behavioral events [71,72]. Likewise, a nation may rapidly enhance it defensive readiness and only later identify and focus on a specific threat. Similarly, upheavals often arise autonomously without supervision, e.g., as spontaneous responses to aversive conditions, and only later organize to meet a specific end. In short, the self is not unitary but hierarchical.

8. Conclusions

These thoughts about thinking do not presume to reduce the brain's complexity to simplicity, but to provide understanding and insight by applying the universal and holistic thermodynamic principle to this specific and intricate system. Despite impressive advances in cognition and neuroscience, the human brain remains for several reasons an exceptionally difficult object of study. Hence there is much room for diverse ideas to account for various functions of brain. In this regard, the universal principle of least-time free energy consumption distinguishes itself by aiming at an all-inclusive understanding of the brain's multitude of functions and structures. The natural model does not only aim at providing a unified theory of the brain but an integrated view of its evolution and operation encompassing its natural setting.

The holistic view of nature recognizes no difference between natural and artificial intelligence, and so deems programming of deterministic and sophisticated algorithms as futile efforts to generate meaningful behavior in response to complicated circumstances. No algorithmic programming alone can approximate intelligence that emerges and continues to evolve along the guiding energetic bias provided by experiencing surroundings. In other words, a robot to be intelligent has to learn how to make its living.

Finally the naturalistic model may also contribute to our understanding of the brain's relationship to the mind [73]. Thermodynamics clarifies the concept of free will by establishing that dissipative decision making is a non-deterministic process [74]. When an individual chooses to pursue one path, other options of free energy consumption will be excluded. Thus, the free will vanishes along with diminishing free energy. Conversely, as long as we have resources, we have responsibilities.

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