Research Article ISSN 2689-1050

Chemical & Pharmaceutical Research

Critique of the "Free Energy Principle" of Consciousness

Gerard Marx[1]* and Chaim Gilon[2]

[1]MX Biotech Ltd., Jerusalem, Israel.

[2]Institute of Chemistry, Hebrew University, Jerusalem, Israel.

*Correspondence:
Gerard Marx, MX Biotech Ltd., Jerusalem, Israel.

Received: 02 Jun 2025; Accepted: 09 Jul 2025; Published: 28 Jul 2025

Citation: Gerard Marx Chaim Gilon. Critique of the "Free Energy Principle" of Consciousness. Chem Pharm Res. 2025; 7(3): 1-7.

ABSTRACT

How does the viable brain transmute caloric energy into consciousness manifest as emotive memory? Apparently, the laws of physics and thermodynamics don't apply.

Here, we summarize and comment on a series of 4 articles published by Friston et al. which purports to rationalize the Free Energy concept applied to sentient consciousness. They suggest that perceptual processes are an emergent property of systems that conform to a free-energy principle and attempt a mathematical description of adaptive changes of biologic phase-boundaries.

We summarize and criticize each of the 4 articles and point out their deficiencies, notably the lack of physiologic relevance. We discuss the options available to the neural net to encode cognitive information and the possibility of epigenetic modifications on the process of memory. We conclude with a short discourse on the tripartite mechanism of neural memory, a biochemical description which conforms to the materials and processes available to neural cells.

Keywords
Mentality, Thermodynamics, Critique, Surprise.

Background

All living creatures experience "consciousness" as "awareness". But not all can remember past stimuli. They can feel (sense) their current environment, but cannot project present experience to the future, cannot remember past feelings.

Responses of primitive cells, such as bacteria, to pleasant or unpleasant feelings, involve moving toward or away from a sensed stimulus, referred to as a "tropism". Like a leaf turning in the sun, it has no psychic experience.

The transduction of metabolic energy into mentality remains the core enigma of neuroscience. The confluence of psychic experience and underlying neuro-chemical processes cannot be ignored. One is a consequence of the other. But the enigma remains: How does the viable brain transmute caloric energy into consciousness manifest as emotive memory?

Classical thermodynamics throws little light on this subject though there have been attempts to drag the concepts of entropy, chaos and information theory into this puzzle [1-6].

A major problem confronting all these efforts is the lack of a notation that signifies emotive states. Absent such, one is at a loss to formulate a code for emotive state.

So too, the Information Theory lacks an evolutionary context with regard to the signaling and encoding of emotive states [7-12]. Music has a notation system that can encode and elicit emotion but it is not physiologic unless one can remember and carry a tune. By contrast, the binary (0 1) or trinary (- 0 +) formats of computers are incapable of encoding emotive states. Ditto all quantum based formulations; they may be entangled but are inherently "demotive."

As we are focused on memory, we inquired: When did the neural creatures develop the talent of "memory"? How does this talent emerge from the activity of neural circuits? In previous works, we summarized the evolution of bacterial signaling with molecular effectors leading to the chemical signaling, which evolved to advanced neural circuits which employ the same molecular signaling molecules (cited below).

Friston et al.,

Here, we examine on the works of Friston and collaborators which proffered a "free energy" rationale. We summarize and comment on a series of 4 articles published by Friston et al., [13-16] which purports to rationalize Free Energy to clarify sentient consciousness. As background, we cite a number of works pertaining to the consideration of Free Energy and chaos to analyze various molecular processes [17,18].

Paper #1:

Friston KJ. Stephan KE, 2007
Free-energy and the brain
Synthese 159: 417–458.

Summary

Discusses model of perceptual inference and learning.
The proposed scheme rests on "*Empirical Bayes and hierarchical models of how sensory information is generated*."

It suggests that perceptual processes are an emergent property of systems that conform to a free-energy principle. They attempt a mathematical description of adaptive changes of biologic phase-boundaries to minimize surprise i.e.

$$Q(\tilde{y}|\alpha) = \ln \quad p(\tilde{y}|\alpha, m) \quad 1$$

where $Q(\tilde{y}|\alpha)$ could be regarded as the adaptive value of a particular exchange, also known as the *log-evidence*. They link *selection in theoretical biology to Bayesian model selection in machine learning*

The free-energy of the system is presented as a *scalar function of sensory and internal states.*

$$\begin{aligned} F(\tilde{y}, \lambda|\alpha) &= -\langle \ln \quad p(\tilde{y}, \vartheta|\alpha)\rangle_q + \langle \ln \quad q(\vartheta;\lambda)\rangle_q \\ &= - \int q(\vartheta;\lambda) \ln \frac{p(\tilde{y},\vartheta|\alpha)}{q(\vartheta;\lambda)} d\vartheta \\ &\geq - \ln \int q(\vartheta;\lambda) \frac{p(\tilde{y},\vartheta|\alpha)}{q(\vartheta;\lambda)} d\vartheta = -Q(\tilde{y}|\alpha) \end{aligned}$$

The following headings are discussed:

Theory= Thermodynamics and biologic systems.
The nature of biological systems
A free-energy bound- *requiring adaptive systems to minimise surprise*
The ensemble and generative densities
The free-energy principle
The mean-field approximation
Optimising variational modes
Perceptual inference*: Optimising* μ_u
Perceptual context and attention: *Optimising* μ_γ
Perceptual learning*: Optimising* μ_θ
Variational action and free-energy
Model optimisation

They suggest that biological systems sample their environment to fulfil expectations generated by the model implicit in their structure (this implies memory). The arguments are couched in impenetrable mathematical formulae.

$$\begin{aligned} F(\tilde{y}, \lambda|\alpha) &= -\langle \ln \quad p(\tilde{y}, \vartheta|\alpha)\rangle_q + \langle \ln \quad q(\vartheta;\lambda)\rangle_q \\ &= - \int q(\vartheta;\lambda) \ln \frac{p(\tilde{y},\vartheta|\alpha)}{q(\vartheta;\lambda)} d\vartheta \\ &\geq - \ln \int q(\vartheta;\lambda) \frac{p(\tilde{y},\vartheta|\alpha)}{q(\vartheta;\lambda)} d\vartheta = -Q(\tilde{y}|\alpha) \end{aligned}$$

Describes hidden causes of environmental stimuli partitioned into three sets that change on a timescale of milliseconds, seconds and minutes, and factorise the ensemble density in terms of marginal densities:

$$\begin{aligned} q(\vartheta) &= \prod_i q(\vartheta_i;\lambda_i) \\ &= q(\vartheta_u;\lambda_u)\, q\left(\vartheta_\gamma;\lambda_\gamma\right) q(\vartheta_\theta;\lambda_\theta) \end{aligned}$$

Surprise the free- energy principle is supposed to explain adaptive behaviour without invoking notions of reinforcement. It is simply sampling the environment so that its sensory input conforms to its expectations (i.e. memory). It asserts that adaptive systems should minimize surprising exchanges with the environment.

Critique

None of the discussion has a biologic flavor. It does not define the "sensory information" on which surprise is predicated. Thus, it does not mention the emotive qualities of "sensory information" or how this is made available without neural memory. Consider, a creature with no memory simply responds to external stimuli. Even bacteria aggregates have been shown to exhibit memory of past experience. "Surprise" implies divergence from a memory of previous experience. Without memory, there can be no "surprise" predicated on expectations based on previous experience. This is a circular argument.

A link is made to theoretical biology as a Bayesian model selection in machine learning, a probabilistic approach used in statistics and machine learning to compare and choose between different statistical models. But it implies little for neural activity eliciting subjective mentality.

The rest of the discussion is an obtuse stream of phrases i.e. "*Formulating that bound in terms of Jensen's inequality requires that function to be a probability density* " which make little sense in terms of identifying the processes underlying neural mentality i.e. Jensen's inequality generalizes the statement that the secant line of a convex function lies above the graph of the function (Wikipedia). This does little to clarify neural processes whereby emotions and memory emerge.

The authors' stated goal is to present a perceptual inference and learning in neural systems.

But in fact, the discussion holds little of neurobiologic interest, but forwards esoteric mathematical formulae which have little to do with physiology and do not reflect mental states.

Paper #2:

Friston KJ. 2009
The free-energy principle: A rough guide to the brain?
Trends in Cognitive Sciences 13: 293-300.

Summary

A free-energy formulation to find principles of brain function is based on conservation laws and neuronal energy. Theorises that any adaptive change in the brain will minimize free-energy, an information theory quantity that bounds the evidence for a model of data. It is greater than the negative log-evidence or 'surprise' in sensory data. It proposes that that *self- organising biological agents resist a tendency to disorder and therefore minimize the entropy of their sensory states*.

It provides a glossary of terms used to describe information as being "divergent", "surprised" or "dense". Box 1 describes the free-energy principle which is somehow a function of sensory input. It provides (Figure 1) a schematic detailing the mathematical quantities that define free-energy.

Discusses "*recognition dynamics*" as parameters relating to *"syntactic efficacy*" and "*synaptic gain*". They overlook the non-synaptic signaling modes available to many dendrites which do not make contact with other neurons, but simply peter out into the neural extracellular matrix (nECM) (Vizi).

A mathematical transformation is presented input sensory i.e. $\dot{\vartheta} = f(\vartheta, \alpha) + w,$ that changes the way the environment is sampled. The environment is described by equations of motion, which specify the dynamics of environmental causes.

Posits that entropy corresponds to suppressing surprise over time.

Subsequent consideration of *Neuronal implementation* employs words such as" *physiological"*, "*anatomical*" and *"synaptic activity*". However, the discussion is irrelevant to any physiologic neural activity which generates mental states. The authors themselves question their approach with a question mark (?) terminating their title.

Critique

The article is a mathematical flavored fantasy of concepts purported to be related to a free-energy principle. Attempts to convince that biological agents engage in some form of "*Bayesian perception*" to avoid surprises. For example, "surprise" necessarily relies on memory. Consider, a creature without memory is not surprised, but has to deal with each stimulus *de novo*, as it occurs, without expectations based on the memory of previous experience.

Their physiologic model is based exclusively on synaptic signaling and ignores non-synaptic modes. This seems to be a persistent model as a modern equivalent to such was recently repeated by Coupland et al. [17] which also ignored the nECM as being relevant to non-synaptic neural communication modes.

They list "Recognition dynamics" to compute the free- energy and derivatives which reduces to first-order differential equations of motion. However, complicated this is subsequently phrased, it makes no sense as a model of brain function; the brain doesn't move.

The Figure I presents a schematic detailing neuronal architecture decorated with mathematical formulae for "*forward and backward connections*". This does nothing to clarify the subjective states characteristic of neural systems.

The Table 1 attempts to explain brain mentality in terms of anatomy, connectivity, synaptic physiology and electrophysiology to account for behavior. Here too, the unrealistic modeling of neural connectivity (i.e. ignoring the nECM and chemical signaling processes). The proposed (Table 2) probabilistic neuronal codes make no physiologic sense. In particular, the enigma of emotive memory remains mysterious.

Paper #3:

Bradcock, Friston et al., (2019)
The hierarchically mechanistic mind:
An evolutionary systems theory of the human brain, cognition, and behavior.
Cognitive, Affective, & Behavioral Neuroscience 19:1319–1351

Summary

The purpose of this review was to suggest a theory of the embodied, situated human brain, called the Hierarchically Mechanistic Mind (HMM). The brain is considered as a complex adaptive system that functions to minimize the entropy of our sensory and physical states via action-perception cycles comprising of four nested levels of biological causation (i.e., adaptation, phylogeny, ontogeny, and mechanism). They glibly leverage this theory to mathematically formulate neural dynamics.

They bring up a brain theory in neuroscience called the free-energy principle. This proposes a schema (their Figure 1), an evolutionary systems theory of psychology, based on 4 levels of causation: adaptation, phylogeny, ontogeny, and mechanism. As gaphic aides, they present tables (Figures 1,2) which seem to be an assortment of words, that are purported to describe an evolutionary systems theory of psychology.

Critique

Though the word "evolutionary" appears in the title, there is little in this article that refers to biologic evolution. Though they tout "evolution" in the title, the substance of the article does not deal with the evolution of the signaling processes from bacteria onward up the Darwinian tree of life. Only the human brain is considered with no mention of the universal signaling processes that govern the life and thought of all creatures, from bacteria upward. The words are there, but they don't make sense. The authors suggest that their "paradigms" allows researchers to integrate advances across different fields. But nothing is presented to substantiate such claims. The words in the table do not present a meaningful pattern. Rather, the words seem to be a random jumble of suggestive terms.

Ditto for their Figure 2, a table presented as a scheme for a hierarchically mechanistic mind.
Still missing is a neurobiologically plausible process.

Their Free-Energy Approach is questionable. The thermodynamic free energy is a measure of the amount of work a system can perform (see Wikipedia), but its application to the process of mentation is not at all clear. The use of phrases such as "*the system will appear to be attracted to particular regimes of state or phase space*" or "*propensity to minimize surprise (resp. free-energy) is the consequence of natural selection: self-organizing systems capable of avoiding such phase-transitions*" are not explanatory of a biologic mechanism, but exercises in linguistic fluidity. They do not address the core enigma of how caloric energy is transmuted to energize the brain's mental activities manifest as emotions and memory. It can be considered as a mysterious phase change, whose qualities we have not yet formulated or rendered mathematically. Throwing in the word "entropy" does little to connect the phenomenon of mentality to thermodynamic "entropy" (i.e. referring to work lost as heat) or the functioning of the brain. This is poetry, not science.

The term "Free Energy principle" refers to a hypothesis that the brain reduces "surprise" or "uncertainty" by predictions to guide behavior. The Figure 3 schematic of the depressed brain is not explanatory regarding brain functioning as a "mentation organ". Thus, we continue our quest for biochemical clarification of mentality.

Paper #4:

Friston K, Da Costa L, Sajid N., Heins C., Ueltzhöffer K., Pavliotis GA.,
Parr T. 2023.
The free energy principle made simpler but not too simple
Physics Reports 1024: 1–29

Summary

One wants a physics of sentience. A concise description of the free energy principle (FEP), in terms of a Langevin equation ending with a Bayesian mechanics. The FEP rests on straightforward results from statistical physics aa described with stochastic differential equations, in which the rate of change of some states touches on the following mathematical treatments:

Bayesian mechanics.
Lagrangian formulation
Fokker–Planck equation
Kolmogorov equation
Schrödinger wave equation
Markov boundary
Helmholtz decomposition
Hessian matrix
Jacobian coupling states
Taylor expansion

They provide *a probabilistic description of a system in terms of a (NESS) density that admits conditional independencies among states.*
Suggest that readings of free energy link nicely to various normative (i.e., optimisation) theories of sentient behaviour.

Their Figure 3. schematic with various mathematical equations illustrates Markov blankets and *self-evidencing points of contact between minimizing variational free energy and other normative theories of optimal behaviour.*

Their Figure 5. schematizes Bayesian mechanics and active inference. Sensory states furnish free energy gradients (often expressed as prediction errors), under some generative model. Neuronal dynamics are simulated as a flow on the resulting gradients to produce internal states that parameterise posterior beliefs about external states.

"*Biological behaviour may be characterised by internal solenoidal flows that do not change variational free energy—or surprisal."*

Their Figure 7 illustrates *expected free energy and active inference and highlights various points of contact with other accounts of sentient, purposeful or intelligent behaviour.*

They propose autonomous action of particles i.e. *free energy contains terms that arise in various formulations of optimal behaviour.*

Posterior beliefs are then used to evaluate free energy and subsequent action to
"simulate the sentient behaviour of precise particles that we have associated with biotic systems."

Critique

The stated goal of this work is to provide a theoretical basis for considering a physics of sentience. That is a roundabout way of talking about consciousness. All sentient creatures exhibit features of consciousness manifest as awareness, emotive responses to their environment, recalled as memory.

The article employs linguistic subterfuges to avoid using the words like "mentality", "cognition" or "emotions", but refers to them indirectly as "*Neuronal dynamics*" and "*normative theories of optimal behaviour"*.

It describes self-organisation *as sentient behaviour that can be interpreted as self-evidencing; namely, self-assembly, autopoiesis or active inference.*

What does this mean?

It suggests that readings of free energy link nicely to various normative theories of sentient behaviour. The article fugues into "math-speak" by providing various equations and referring to formulae named after mathematicians listed above.

As far as we, the reviewers, are concerned, this 2023 attempt to rationalize mentality is "far off the mark". We note the following lapses.

1. No way of coding for emotions.
2. No process for encoding persistent memory.
3. No recognition of non-synaptic signaling.
4. No recognition of the nECM and its function in neural signaling.
5. No physiologic relevance.

Thus, this effort to yoke the Free Energy Principle to the service mentality does not convince.
Rather, it befuddles the reader with obscure mathematics that have no relevance to emotive memory. Again, more poetry than science.

Tripartite Mechanism [19-27]

To be original, one is encouraged to think "out of the box". But we are doing the opposite and thinking into a box i.e. a chemographic representation of the *cuinfo* within the nECM, represented as box rich in electrons that attract metal cations (i.e. address). The immobilized metal cations in turn bind NTs to form complexes that encode emotive memory (Figure 1).

Arguments from thermodynamics, such as free energy or mathematical formulations, lack physiologic relevance. Maxwell's cat notwithstanding, there is currently no unified theory of molecular and cellular dynamics that can give rise to mentality. Recall that the free energy of classical thermodynamics relates to the work (or heat) that can be extracted from a closed system at a given temperature.

$$\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ$$

where G energy available for non-pressure-volume work, H is enthalpy, T is absolute temperature and S is entropy. But this is far from the usage of Friston et al. The brain does not "work" and mentality cannot be described by just alluding to free energy clothed in constructs from statistical physics.

Consciousness, emotions and memory are examples of emergent properties of the brain that cannot be fully explained by the laws of physics or encoded by mathematical formulations.

Epigenetics

Epigenetics literally refers to processes that occur after DNA controlled structures have been formed (i.e. biosynthesis of neuron and nECM). What we want to know is how (epigenetic) experience is encoded for recall? As we are considering a biological process, we are driven into the realms of chemistry applied to biology.

Some have attempted to ascribe memory to epigenetic process, such as acetylation of histones in the hippocampus [28-32]. This was interpreted as indicating that chromatin modifications dictated the recruitment of "*sparse populations of neurons constituting an*

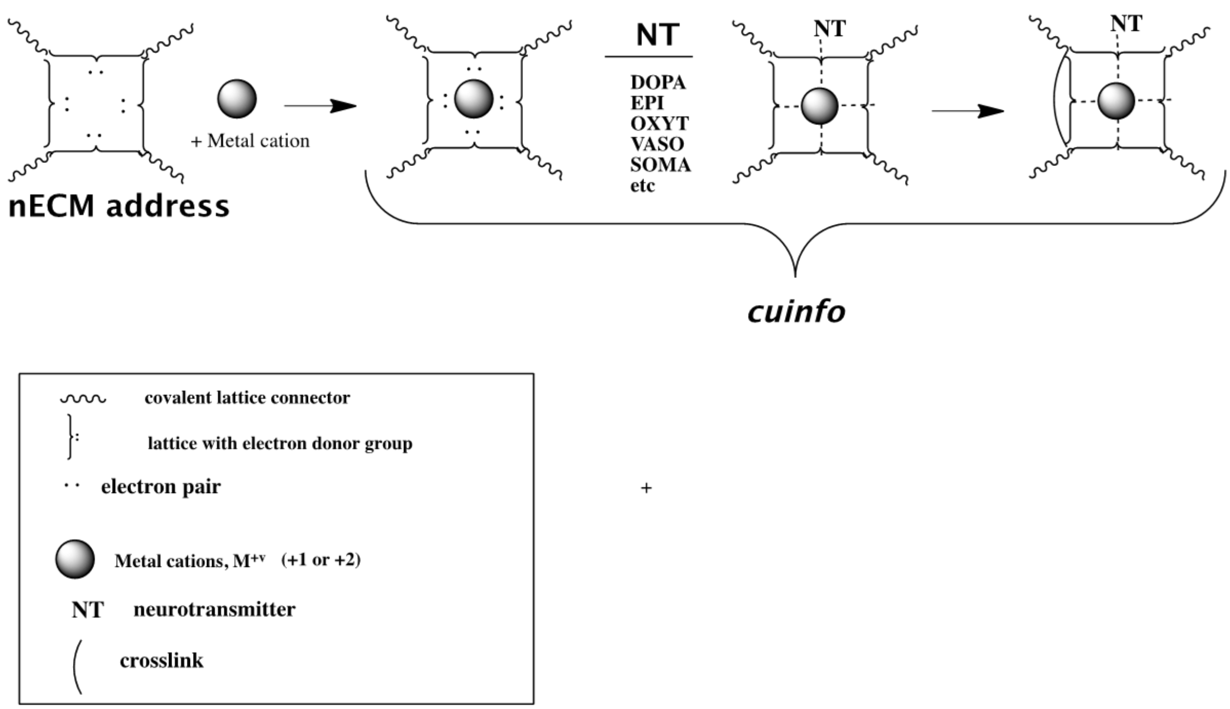

Figure 1: Chemographic representations of the reaction of a nECM at an electron rich site ("address") binding site for a metal cation, to form a cognitive unit of information (*cuinfo*). The complexation of a neurotransmitter (NT) to the entrapped metal cation confers emotive context to the *cuinfo*. Subsequent crosslinking confers greater stability to the complex, reflected by the persistence of memory, particularly those with great emotive contex.

engram". Epigenetic regulation could have significant indirect effects on the neural ECM through its influence on gene expression and cellular function. While this may be true, it is too general to serve as a statement of a memory mechanism. Also, it is hard to imagine that a single derivatization process could encode the complex emotive states experienced and recalled by a neural circuit. What then is memory?

Encoding Memory: Tripartite mechanism

In spite of the many drugs that affect memory and mood, no chemist has had the effrontery to suggest that basic mental processes are chemical. Notwithstanding, we have proposed such a molecular mechanism, the tripartite mechanism. This idea would remain in the limbo of "hypothesis" were it not for the electrodes prepared by our colleagues (Shlomo Yitzchaik group at Hebrew University) [26-28]. They have shown experimentally that NTs coated on impedence electrodes can be used to detect traces of metals. Similarly, saccharide coating on electrodes behaved similarly, electrodynamically detecting metal cations. Such coated electrodes make more credible the idea that neural memory is based on a code comprising metal-centered complexes within the nECM.

Of course, the neural code is exponentially more complex than the binary code of computers (n=2), with more than 10 metal cations, more than 80 NTs and a near infinity of polysaccharide isomers units comprising the nECM.

<u>Codes (Info/ Cog-info)</u>
binary n=2
neural n= f(# metals) f(# NTs) f(# saccharide isomers) {>100}

There are many gaps in our knowlege of the general mechanisms of epigenetics which affects memory. The exact mechanism of memory is still not known [29-32]. As for the neural process for memory, we have identified the active components that generate memory (i.e. the static neural cells (neurons + astrocytes), the static nECM and the diffusible dopants (metal cations and NTs) (see tripartite mechanism). Describing the general process of epigenetics does not imply that one can detail the exact mechanism(s) by which it affects memory.

Unlike the Information Theory of the binary code, there is no theory whereby cognitive information can be encoded with >100 effectors to represent emotive memory. Thus, the engram may be real and modulated by sparse sets of neural cells, but we have not yet grasped its essence. We continue our quest for enlightenment regarding the mechanism of emotive memory.

Conclusion

Memory and "thought" are different manifestations of the same process.

Consciousness is evanescent…it evaporates like bubbles in the sea of experience, of which only a residual physical trace remains, as memory, *the "engram*". Some have proposed the existence of "memory molecules" [18] but a credible, detailed case has not yet been forwarded.

References

1. Penrose R. Quantum physics and conscious thought. In. Quantum implications: Essays in honour of David Bohm (Eds. Hiley and Pearl). 1987.
2. Roberson ED, Sweatt JD. A biochemical blueprint for Long-Term Memory Learning & Memory. 1999; 6: 381-388.
3. Collell G, Fauquet J. Brain activity and cognition: A connection from thermodynamics and information theory. Front. Psychol. 2015; 6: 818. DOI: 10.3389/fpsyg.2015.00818
4. Tuszynski JA. The Emerging Physics of Consciousness. Springer, Berlin, DE. 2006.
5. Rosenblum B, Kuttner F. Quantum Enigma: Physics Encounters Consciousness. Oxford University Press, NY. 2011.
6. Ampel BC, Muraven M, McNay EC. Mental Work Requires Physical Energy: Self-Control Is Neither Exception nor Exceptional Front. Psychol. 2018; 9: 1005. DOI: 10.3389/fpsyg.2018.01005
7. Landauer R. The physical nature of information. Physics Letters. 1996; 217: 188-193.
8. Tononi. Consciousness as integrated information: A provisional manifesto. Biol Bull. 2008; 15: 216-242.
9. Howard N, Hussain A. The fundamental code unit (FCU) of the brain: Towards a new model for cognitive geometry. Cognitive Computation. 2018; 10: 426-436.
10. Hughes DT, Sperandio V. Inter-kingdom signalling: communication between bacteria and their hosts Nat. Rev. Microbiol. 2008; 6: 111-120.
11. Dahaene S. Consciousness and the Brain. Deciphering How the Brain Codes Our Thoughts. Viking Press, New York. 2014.
12. Von der Malsburg C. Concerning the Neuronal Code. J. Cognitive Science. 2018; 19: 511-550.
13. Friston KJ, Stephan KE. Free-energy and the brain Synthese. 2007; 159(3): 417-458.
14. Friston KJ. The free-energy principle: A rough guide to the brain? Trends in Cognitive Sciences. 2009; 13: 293-300.
15. Bradcock PB, Friston KJ, Ramstead MJD, Ploeger A, Hohwy J. The hierarchically mechanistic mind: An evolutionary systems theory of the human brain, cognition, and behavior. Cognitive, Affective, & Behavioral Neuroscience. 2019; 19: 1319-1351.
16. Friston K, Da Costa L, Sajid N, Heins C, Ueltzhöffer K, et al. The free energy principle made simpler but not too simple Physics Reports. 2023; 1024: 1-29.
17. Izquierdo I, Bevilaqua LRM, Rossato JI, Bonini JS., Medina JH, et al. Cammarota M. Different molecular cascades in different sites of the brain control memory consolidation. TRENDS in Neurosciences. 2006; 29: 496-505.
18. Dunning J, During MJ. Molecular mechanisms of learning and memory. Expert Reviews Molec. Med. 2003.

19. Marx G, Gilon C. Tripartite mechanism of neural memory: Proof-of-concept with neuromimetic impedance electrodes. Biomedical Research and Clinical Review. 2020; 1(3): 21. DOI: 10.31579/2692-9406/021
20. Marx G, Gilon C. Encoding neural memory. Front Drug Chem Clin Res. 2020. DOI: 10.15761/FDCCR.1000149
21. Marx G, Gilon C. Interpreting neural morphology. Acta Scientific Neurology. 2020; 3: 1-4.
22. Marx G, Gilon C. Quantum considerations of neural memory. In: Quantum Boundaries of Life. Poznanski RR & Branda E. (Eds), Elsevier, Amsterdam. 2020; 82.
23. Marx G, Gilon C. The Molecular Basis of Neural Memory. Part 11. Chem-electric Write /Read Processes. J. Neurosurg. Imaging Techniques. 2020; 6: 283-301.
24. Marx G, Gilon C. The molecular basis of neural memory. Part 10. The sins and redemption of neurobiology. J Neurol Neurocrit Care. 2018; 1: 1-7.
25. Marx G, Gilon C. The molecular basis of neural memory. Part 9: Defining the Engram Res Med Eng Sci. 2018; 7: 000651. DOI: 10.31031/RMES.2018.07.000651
26. Tadi KK, Alshanski I, Mervinetsky E, Marx G, Petrou P, et al. Oxytocin-monolayer-based impedimetric biosensor for zinc and copper ions. ACS Omega. 2017; 2: 8770-8778.
27. Alshanski I, Sukhran Y, Mervinetsky E, Unverzagt C, Yitzchaik S, et al. Electrochemical biosensing platform based on complex biantennary N-glycan for detecting enzymatic sialylation processes. Biosens Bioelectron. 2021; 172: 112762.
28. Marx G, Gilon C. Tripartite mechanism of neural memory: Proof-of-concept with neuromimetic impedance electrodes. Biomedical Research and Clinical Review. 2020; 1(3): 021. DOI: 10.31579/2692-9406/021
29. Krabbe S. Epigenetic control of memory formation. Science. 2024; 385: 367-368.
30. Santoni G, Astori S, Leleu M, Glauser L, Zamora SA, et al. Chromatin plasticity predetermines neuronal eligibility for memory trace formation. Science. 2024; 385: 408-409.
31. Qureshi IA, Mehler MF. Understanding neurological disease mechanisms in the era of epigenetics. JAMA Neurol. 2013; 70: 704-710.
32. Freudenthal RAM, Romano A, Baez MV. Editorial: Changes in molecular expression after memory acquisition and plasticity. Looking for the memory trace. Front. Mol. Neurosci. 2020; 13: 50-53.