Physics of Organismic Storage

Introduction

Current neuroscientific models of memory usually view memory as a function, for example as a reactivation of earlier activation patterns, as a symbolic encoding, or as the recognition of stored content. In this perspective, memory is primarily understood as a functional change in state or as the re-availability of semantic or sensory information that is stabilized by synaptic plasticity or molecular modulation. What is usually missing is a physically sound description of what "storage" actually means. In the position represented here, therefore, a radical change of perspective is undertaken: memory is not the reappearance of a stored symbol, but the material, directed restructuring of the system itself. In this sense, memory is not a passive archive, but the active expression of a structural transformation. Storing means that a system has changed irreversibly – and this change is not metaphorical, but physically real.

Memory as a material trace

In this view, memory is not understood as an internal image or as a symbol carrier, but as the concretely measurable difference between two physical states of an open system. A stimulus, an experience or a behavior does not lead to the storage of "information" in the metaphorical sense, but to the irreversible reorganization of the system architecture. This reorganization can take place at different levels: molecular, cellular, network dynamics, or epigenetic – and it can be physically grasped in all cases. At the molecular level, for example, the configuration of proteins, enzymes or receptors changes. A well-documented example is receptor phosphorylation, in which the function or position of a membrane receptor is changed by phosphate group binding. This affects neuronal excitability and creates structural foundations for synaptic enhancement or attenuation. It is crucial that such changes are not to be understood as temporary functional modulation, but as physically manifest conversion measures. A modified receptor can change the responsiveness of a synapse over longer periods of time, for example by modulating the probability of excitatory or inhibitory transmission. This creates a persistently different reaction landscape in the neural network, which differs materially from previous states. Such rearrangements are not merely biochemical reactions, but structural repositioning within the functional space of a system. They mark the material trace of an experience and anchor it at the subcellular level. Equally relevant are prion-like proteins such as CPEB, which form configuration-stable aggregates in activated form and can thus stabilize long-term states (Si

et al., 2003). The importance of this mechanism lies in its unique ability to maintain a functional state over long periods of time without a permanent supply of energy. The aggregates formed by CPEB proteins do not represent information in the classical sense, but establish a permanent structural configuration that is essential, for example, for local protein synthesis in dendrites. Their prion similarity does not mean pathology, but functional self-stabilization: a state, once achieved, reproduces itself by changing the environmental conditions in such a way that it is maintained. In this way, these aggregates embody a form of physical memory in which experience is anchored as an energetically fixed structure. Their existence impressively demonstrates that neuronal memory must be understood not only at the electrophysiological, but above all at the molecular-structural level. Protein folding, for example by chaperones, also leads to new functional properties at the cellular level. Cellularly, this remodeling takes place, for example, in the growth or retraction of dendrites, in synaptogenesis or synaptic pruning. The dendritic spine structure can change significantly depending on stimulation or inactivity, which affects functional connectivity (Yuste & Bonhoeffer, 2001). Network dynamics create stable activation patterns that operate as functional units. Recurring activation leads to coherent oscillation, which in turn further modulates structural plasticity. Finally, epigenetic mechanisms such as DNA methylation or chromatin remodeling rely on transcriptional control to change genetic expression patterns in the long term. These processes do not encode the content, but rather change the accessibility of certain gene sequences – for example, through histone modification or through non-coding RNAs that form regulatory networks (Day & Sweatt, 2011). What all processes have in common is that they do not cause the "storage" of an object, but a transformation through which the system takes on a new energetic and structural configuration. Receptor phosphorylation changes the sensitivity and responsiveness of the neuronal membrane through targeted molecular interventions. These changes deeply interfere with electrophysiological connectivity and define new pathways for signal processing. Protein folding by molecular chaperones is another example: Here, an alternative configuration of a protein is stabilized by external or internal stimuli, which henceforth opens up new possibilities for interaction. This is particularly evident in local translation at dendritic spines, where configuration-dependent proteins create the structural prerequisite for a persistent change in the synapse. These processes lead to a regional reprogramming of functional competencies in the neural network.

Synaptic pruning, in which unused or inefficient synapses are regressively restructured, is also an expression of systemic optimization based on

experienced relevance. This is not additive storage, but integrative selection and elimination that does not expand the system, but restructures it. At the network dynamic level, coherent activation patterns can be identified, whose temporally repeated emergence leads to stable oscillations. These oscillations produce amplification effects in themselves, which contribute to the perpetuation of the underlying circuits. Synchronized activity clusters can thus be understood as functional memory units whose stability is directly tied back to their structural coupling.

Finally, epigenetically storage shows itself to be a reorganization of the logic of access to genetic information. DNA methylation shifts the transcription profile, histone modification changes the chromatin structure, non-coding RNAs act as delicate control instances that form feedback loops in gene expression. These changes are not only temporary, but can be detected stably over cell generations, for example in prenatal stress processing or maternal care (cf. Meaney, 2010). In all the examples mentioned, the focus is not on the mapping or storage of something, but on the material imprinting of a system state.

The conclusion for the model developed here is clear: memory is not a semantic category, but a physical state that results from the conditions of systemic openness, energetic dissipation and structural self-modification. The system does not save by archiving content, but by changing irreversibly. Structure is thus not the means of representation, but the trace of passage through experience.

In contrast to symbolic models of memory, which postulate external information as a retrievable image, a structuralist paradigm is advocated here: memory is the material consequence of a system change triggered by experience. The continuity between stimulus uptake, processing and storage is ensured by physical processes that are characterized by energetic feedback, molecular self-amplification and structural persistence.

Against this background, short-term memory, long-term memory and forgetting can be understood as different degrees of stability of such restructuring mechanisms. Short-term memory content is based on volatile, energetically unstable state changes such as ion shifts or reversible phosphorylations, while long-term storage requires profound structural reorganizations that are stabilized in the long term by protein synthesis, gene expression or autocatalytic processes. Forgetting in turn does not represent a "deletion", but a restructuring in which earlier conversions are superimposed, decoupled or embedded in new functional contexts. It is a second transformation, not a regression.

Thermodynamics and energetic vectorization

A physically sound understanding of memory requires embedding in the thermodynamics of open systems. Living systems are far from thermodynamic equilibrium and are characterized by permanent energy absorption, conversion and release. They dissipate energy in the form of heat, molecular movements, and chemical reactions to maintain their internal order. Structure is not created despite, but because of this dissipation. In this context, storage is a form of energetic path dependency, in which energy is not only consumed, but invested in the form of a functional structure.

A central example is the energetically driven stabilization of neuronal configurations by autocatalytic signal cascades. These can be triggered by initial stimuli, activate intracellular second-messenger systems such as Ca2+ signaling pathways or cAMP cascades, and lead to stable molecular states via recursive feedback. These autocatalytic processes are not merely a consequence of chemical reactions, but mechanisms of energetic structural solidification. In the thermodynamics of living systems, one speaks of dissipative structures (Prigogine), which organize and maintain themselves under the flow of energy. Hebb's learning is such a dissipative structure: Repeated simultaneous activation of two neurons energetically lowers the threshold for future joint activation. This energetic optimization creates synaptic reinforcements, which are not to be interpreted by chance, but as a consequence of directed energy processes.

Selective stabilization by repeated stimulation can also be interpreted thermodynamically: It corresponds to an energetic amplification of pathways in which energy flow has already been established. The construction of stable engrams, as demonstrated in the optogenetic reactivation of hippocampal memory groups (Tonegawa et al., 2015), is thus not a symbolic representation, but the fixation of energetically favored structural patterns. In all of these examples, memory is the consequence of directed energy flows that create a physical difference that persists. Each experience changes not only the state of the system, but also its energetic topology. In this view, memory is the vector of this structural vectorization – a thermodynamically stabilized trace of experience that is realized not through recognition, but through reconstruction.

This energetic perspective allows for a new description of the experience itself. It is not understood as an abstract exchange of information, but as a thermodynamically oriented change of direction of a living system. Every experience generates an entropy difference, the structural resolution of which manifests itself as material transformation. In this sense, memory is nothing

more than the directed thermalization of difference: the trail remains because the system has invested energy to produce a certain order – an order that exists against the general tendency towards entropy.

Genomic storage as a deep restructuring

The concept of structural storage cannot be limited to neuronal processes, but must be extended to the genome. Here, too, environmental stimuli lead to directed, stable conversions that are not symbolically encoded, but occur as modifications of the genetic expressive architecture. Epigenetic mechanisms such as DNA methylation, histone modification, RNA interference or transposon activation produce structural state changes that can be transgenerationally transmitted under certain conditions. These processes are not static switching of genetic programs, but dynamic reorganization processes at the molecular level. Experience is not stored in the genome as an isolated event, but as a systematically embedded restructuring of regulatory relationships.

For example, DNA methylation alters the transcriptional activity of entire gene clusters by influencing the accessibility of promoter regions. These methylations arise as a result of specific stimuli – such as maternal care, stress or nutrition – and permanently shape gene expression in relevant brain regions (cf. Meaney, 2010). Histone modifications reorganize the chromatin structure, which leads to a spatial restructuring of the genome: certain sections become openly accessible, others are permanently compacted. This gives rise to functional reaction patterns that do not act through information, but through spatial-structural difference. Non-coding RNAs (e.g. miRNAs or lncRNAs) also generate a new regulatory level via feedback loops, which anchor experiences in molecular feedback architectures.

A particularly impressive example is the transgenerational transmission of epigenetic states, for example in prenatal stress processing, where environmental experiences of the mother lead to stable epigenetic modifications in the brains of the offspring. Such cases show that experience not only leaves traces in the individual nervous system, but can also be burned into the genetic reaction system. This form of memory is not mentally but structurally, not symbolically but materially encoded.

The conclusion for our model is clear: the genome is also a repository – not in the sense of a symbolic code, but as an energetically open system that integrates experience through targeted restructuring of its regulatory architecture. Epigenetics is thus not an additional level to genetics, but an

expression of a general principle: structural change under conditions of systemic openness. Genomic memory is deep, slow and systemic – it structures the prerequisites of neuronal plasticity and is thus the basis of all higher forms of individual learning ability. This logic can be transferred to other organizational levels: cell groups, tissues and entire organs also show adaptive restructuring that reacts to systemic experiences. For example, muscular plasticity can be understood as a response to mechanical stress, in which repeated stimuli lead to structural changes at the cellular and extracellular level. Hormonal control systems such as the hypothalamic-pituitary axis also permanently change their reaction patterns due to chronic irritation or stress. Even the heart shows restructuring processes on a structural level in response to pressure and volume loads. In all these cases, the reaction is not merely functional, but is associated with material restructuring – be it in the form of gene expression shifts, cellular rearrangements, or long-term matrix remodelling. These phenomena suggest that the principle of structural storage described here is not the domain of the brain or the genome alone, but represents a universal organizing principle of living systems.

Valence coupling as a principle of bonding

Structural storage is based on a general principle of physical bonding: valence coupling. In chemistry, this term describes the ability of atoms to bind to other atoms via electron pairs and thus form stable molecules. These chemical bonds are not only functional compounds, but energetically defined states that are characterized by specific configurations and feedback ratios. They create a material coupling that, once established, produces a new emergent property: structure. This principle continues in the neuronal area as synaptic coupling. When neurons are active at the same time, the likelihood that their synapses will be strengthened increases – a physical consequence of simultaneous electrochemical activity that is reflected in the material structure of the synapse. Synaptic plasticity is therefore not a symbolic process, but a stabilized coupling process.

At a higher level, comparable mechanisms can be seen in systemic forms of attachment, for example in the formation of behavioral routines or cognitive schemata. Repeated co-activations – for example when learning motor movement sequences – lead to permanent, structurally stable connection patterns in the neural network. These patterns are not representations, but stabilized pathways for excitation propagation. Here, too, memory is not a coding, but a directed coupling that manifests itself materially – for example in changed synapses, spines or network architectures. The psychological concept of association can thus be interpreted as a system-theoretical valence coupling:

what is experienced, activated or used together binds itself materially. This bond is physically grounded and energetically maintained, not symbolically or semantically mediated. Representation, understood in this way, is a retrospective interpretation of a real attachment pattern.

These coupling processes can be strengthened and consolidated by recursive dynamics. Hebb's principles, according to which joint activity leads to increased synaptic connection, are an expression of this valence logic. Likewise, the formation of sensory-motor schemata in early childhood can be interpreted as valence coupling: repeated coactivation leads to the structural anchoring of attachment patterns, which later remain retrievable as stable routines without the need for symbolic representation. The experience itself – i.e. the experience of a relation – is the energetically initiated, physically anchored cause of structural coupling. This view abolishes the assumption of representation and replaces it with a concept of emergent attachment stability based on real physical processes.

Demarcation of representation and symbolism

The model represented here is in contrast to classical models of representation. While these assume the existence of inner images, symbols or engrams, the structural physics approach does not postulate a symbolic instance. Classical theories – such as those of the semantic network or propositional coding – implicitly presuppose an inner subject that retrieves or interprets stored content. These models often convey a dualistic heritage, in which the mental is attributed to an inner observer who has representations. The structural physics model, on the other hand, negates the necessity of such an inner theatrical metaphor: there is no "image in the head" that is recalled – there is only the structurally changed state of the system itself.

Newer approaches such as predictive coding, which interprets learning as top-down modeling of future perception, also continue to operate with a metaphorical concept of information that presupposes representation. Although they emphasize dynamic feedback, they are based on the basic idea that the brain generates hypotheses about the world in order to "explain" sensory stimuli. The model developed here goes one step further: it replaces the idea of cognitive modeling in favor of energetic, structural vectorization. Experience does not change a hypothesis, but the material state of the system. Learning is not an epistemic process in the sense of gaining knowledge, but a physical restructuring process that is stabilized by dissipation.

In this paradigm, memory is not access to a representation, but the persistence of material difference. This difference is not interpretive, but real: it manifests itself in altered membrane potentials, recombined gene expression patterns, remodeled synapses, and reorganized networks. It is empirically accessible without having to draw in a symbolic level. Thus, the structural physics model provides a completely ontological description of memory – not as a function or model, but as an irreversible expression of systemic change. It replaces the metaphorical terms of traditional cognitive science with thermodynamically and structurally comprehensible concepts. Structure replaces representation, restructuring replaces access, and system state replaces symbolic content.

Implications and empirical perspectives

This view has far-reaching consequences for research. If memory is understood not as a symbolic recall system, but as a structural transformation, the methodology of empirical studies also shifts. It is not enough to record cognitive performance behavioristically or to measure electrical activity patterns – rather, the focus must be on material restructuring processes. These include, for example, high-resolution morphometry (to investigate dendritic structural changes), proteome mapping (to identify permanent molecular configurations in synapses) and epigenomic analyses (to detect sustainable modifications in gene regulation). This makes it clear that memory is not the "output" of a cognitive system, but the physical state of a dynamically restructured organism.

The extension to non-neuronal cell types also opens up new perspectives. Glial cells, immune cells or epithelial cells show adaptive remodeling that can be interpreted as a form of structural memory. In immunology, for example, we have long spoken of "immunological memory", but this is hardly understood in the sense of symbolic storage. Rather, it is differential receptor formation, chromatin-based stabilization of activation states and epigenetic presets. This analogy makes it clear that memory is not an exclusive domain of the brain, but a systemic ability of structurally changing systems.

The model is particularly fruitful for the conception of artificial intelligence. So far, many AI models have been based on symbolic representations, algorithmic processing, and abstract optimization criteria. A memory model understood in terms of structural physics, on the other hand, would require an AI system not to process information, but to change its own structure recursively – depending on energy flows, stimulus density, systemic coupling and vectorization. Only systems that restructure themselves under dissipative conditions can develop something like experience, adaptation or historically anchored behavior.

A non-symbolic AI would therefore have to be thermodynamically open, i.e. able to absorb energy flows and transfer them into structural conversions. It would have to be plastically configured, i.e. not only have parameters, but also materializable coupling relationships. And it would have to be capable of feedback, so that earlier structural changes influence the future way of reacting. In such a model, learning would not take place as statistics or the application of rules, but as a directed conversion process within an energetically open artificial organism. This makes AI a structural system, not an information-processing device. This opens up new paths in the development of biologically inspired, self-organizing architectures.

Result

Memory is not a function, but a physical property of living, energetically open systems. It is not created by coding, but by directed conversion under conditions of energy flow, systemic coupling and structural feedback. Saving is not a symbolic process, but a material transformation that leaves its mark on the configurations of the system. Structure replaces representation, stabilization replaces retrieval, and persistence replaces information.

In this perspective, memory is neither a storage place nor a data format, but the physically realized difference between the state before and after an experience. This difference is reflected in molecular rearrangements, cellular restructuring, network dynamic reconfigurations and epigenetic inscriptions. Memory is thus not a concept of access, but a phenomenon of materiality: what has been experienced has changed the system – not in terms of content, but structurally. Every stimulus that brings about a change becomes a trace; every trace that remains becomes a memory.

The consequences for research and technology are far-reaching. They concern not only the empirical recording of biological plasticity, but also the understanding of intelligence, learning, adaptation and memory beyond symbolic logics. An AI system that really learns has to change. A biology that remembers has to rebuild. And a subject that recognizes itself must be structurally integrated into itself.

Ultimately, memory thus becomes the thermodynamic vector of experience: a coagulated story in the fabric of the structure.

Literature

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