OPEN ACCESS

Electronics Systems LETTER

The Innovation

Bioinspired iontronic architectures for neuromorphic intelligence

Xiang Li,[1] Zhong Lin Wang,[1] and Di Wei[1,*]

[1]Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing 101400, P.R. China

*Correspondence: weidi@binn.cas.cn

Received: November 7, 2025; Accepted: May 11, 2026; https://doi.org/10.1016/j.xinn.2026.101424

© 2026 The Authors. Published by Elsevier Inc. on behalf of Youth Innovation Co., Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Citation: Li X., Wang Z.L., and Wei D. (2026). Bioinspired iontronic architectures for neuromorphic intelligence. The Innovation **7(7)**, 101424.

Dear Editor,

The human brain operates as an embodied ionic system fundamentally distinct from silicon-based neuromorphic approaches, which remain disembodied and energy-intensive due to von Neumann architectures that separate memory and computation and exceed the brain's ∼20 W power budget by orders of magnitude. By contrast, the brain couples nanoscale ionic transport, chemical reactions, and energy flow to achieve perception, learning, and decision-making. Inspired by this principle, iontronic systems use ions as charge carriers to replicate neural functions: nanoconfined channels emulate Ca^{2+}-gated neurotransmission, asymmetric electrical double layers (EDLs) encode memory and directional signaling, and memristive ionic networks integrate plasticity and feedback. These hierarchical architectures establish a physical basis for embodied intelligence, where computation emerges directly from matter and charge. Iontronics thus offers a path toward energy-efficient, self-organizing, brain-inspired neuromorphic matter.

The Blue Brain Project, launched by EPFL in 2005 and later expanded into the EU's Human Brain Project, aimed to digitally reconstruct the mammalian brain by integrating neuroscience, computation, and informatics. These efforts relied on electronic architectures that translated neuronal morphologies and synaptic dynamics into circuit equations executed on supercomputers, driving major advances in brain modeling and shaping artificial intelligence (AI). Yet a fundamental gap remains between simulation and embodiment. The biological brain operates within a ∼20 W power budget, whereas simulating even a single neocortical column on IBM's Blue Gene/Q requires megawatts, an energy difference of over six orders of magnitude. This disparity originates from the von Neumann separation of memory and computation, which imposes repeated data transfer under centralized control, unlike the brain's asynchronous, event-driven, and locally powered operation. Typical electronic neuromorphic devices based on ferroelectric and two-dimensional materials partially bridge this gap by reproducing synaptic plasticity and in-memory learning while retaining key practical advantages such as mature integration, high speed, and established manufacturing infrastructure. However, electrons remain the sole information carriers, with a centralized energy supply and computation based on charge displacement rather than local electrochemical evolution, resulting in functional mimicry without physical embodiment and an intelligence detached from its material substrate. Recent ionic-electronic hybrid platforms partially address these limitations by using an external bias to regulate interfacial redox reactions and EDL dynamics, enabling ionic processes to modulate electronic transport and co-localize sensing, memory, and computation.[1] Building on this progress, achieving adaptive, low-power computation requires a shift toward self-powered ionically coupled systems driven by intrinsic interfacial electrochemical dynamics, in which matter, energy, and information are intrinsically linked.

Unlike disembodied, electron-based intelligence, where information processing is largely abstracted from material dynamics and encoded in charge flow, the biological brain operates as an embodied system in which ions act as the primary information carriers. Beyond charge, ions encode information through their valence states, chemical identities, and concentration gradients, directly coupling physical state evolution with information processing. At neuronal interfaces, ionic motion within nanoscale EDLs couples with local fields and interfacial reactions, enabling signal transmission, memory formation, and energy conversion within the same processes. These processes operate at picojoule-scale energy per neuronal event, providing a physical basis for the brain's energy efficiency and multidimensional information encoding.

Realizing embodied intelligence requires returning to the brain's fundamental unit: the synapse (Figure 1). Beyond a communication interface, the synapse functions as a nanoscale reaction field where perception, memory, and computation converge through coupled ionic and electrochemical dynamics. Inspired by this principle, iontronic architectures integrate sensing, memory, and computation into physical units, forming the basis of low-power, matter-based intelligence. At the channel level, nanoconfined ion transport mimics Ca^{2+}-gated influx; at the interface level, asymmetric EDLs generate memristive plasticity; and at the network level, iontronic arrays enable distributed, in-memory processing. Coupling across these levels allows matter, energy, and information to coevolve, establishing a physical substrate for learning and adaptation and enabling a transition from disembodied AI to embodied intelligence. In the following sections, we outline this hierarchy from nanoconfined ion transport to asymmetric EDLs and finally to ionic memristive networks for adaptive neuromorphic learning.

SYNTHETIC SYNAPTIC ARCHITECTURES FOR CONTROLLED ION TRANSPORT

In biological synapses, voltage-gated Ca^{2+} channels convert electrical excitation into chemical signaling within the nanoscale EDL of the neuronal membrane. Ionic migration, field modulation, and interfacial chemistry are intrinsically coupled within the Debye length, with each ion-flow event simultaneously dissipating energy and encoding information, forming the physical basis of energy-efficient neural computation. Artificial nanofluidic channels, defined as nanochannels with dimensions comparable to the Debye length, replicate this coupling by confining ion transport within overlapping EDLs, where surface charge and geometry dictate selectivity and directionality.[2] Within these nanoconfined spaces, partially dehydrated ions migrate under osmotic or chemical potential gradients, converting ionic motion into electrical energy via interfacial redox coupling, revealing that communication and energy transduction share a common ionic origin. Under optical or chemical stimulation, these channels evolve from passive conduits to active sensory elements; for example, photoresponsive halide channels encode color via wavelength-specific ion flux, realizing optical memory at the ionic level.[3] Persistent ionic polarization after stimulation manifests non-volatile states analogous to long-term potentiation. At the circuit level, asymmetric or gated nanochannels modulate ion-flow polarity and magnitude, functioning as ionic rectifiers and transistors for logical operations.[4] The transition from osmotic-driven transport to gate-controlled conduction marks the shift from energy conversion to computation, where excitation and inhibition coexist within a single iontronic framework. Collectively, these processes establish a continuum of power generation, sensing, and logic, all arising from nanoconfined ionic motion. Each ion migration event inherently couples matter, energy, and information, where charge refers to ionic carriers and interfacial accumulation within EDLs, matter denotes nanoconfined channels and interfacial architectures that regulate ionic motion, and energy represents the underlying electrochemical driving forces, including osmotic, chemical, and electrostatic potentials, which not only drive ion transport but also modulate and encode system states. This coupling grounds ion transport and interfacial dynamics, rendering the nanofluidic channel a synthetic analog of the neuronal membrane, where intelligence emerges from the dynamic evolution of charge, matter, and energy.

ASYMMETRIC EDLs AS SYNTHETIC SYNAPTIC INTERFACES

Neural communication relies on interfacial asymmetry: Ca^{2+} influx generates local concentration gradients that trigger vesicle fusion and neurotransmitter release. Inspired by this principle, asymmetric EDLs in triboiontronic systems can be defined as non-equilibrium interfaces with spatially non-uniform ion distributions, charge densities, and electrostatic potentials. Such asymmetry arises from triboelectric-induced polarization, in which solid-solid contact electrification generates transient interfacial electric fields that perturb interfacial equilibrium. Coupled with controlled solid-liquid contact dynamics,

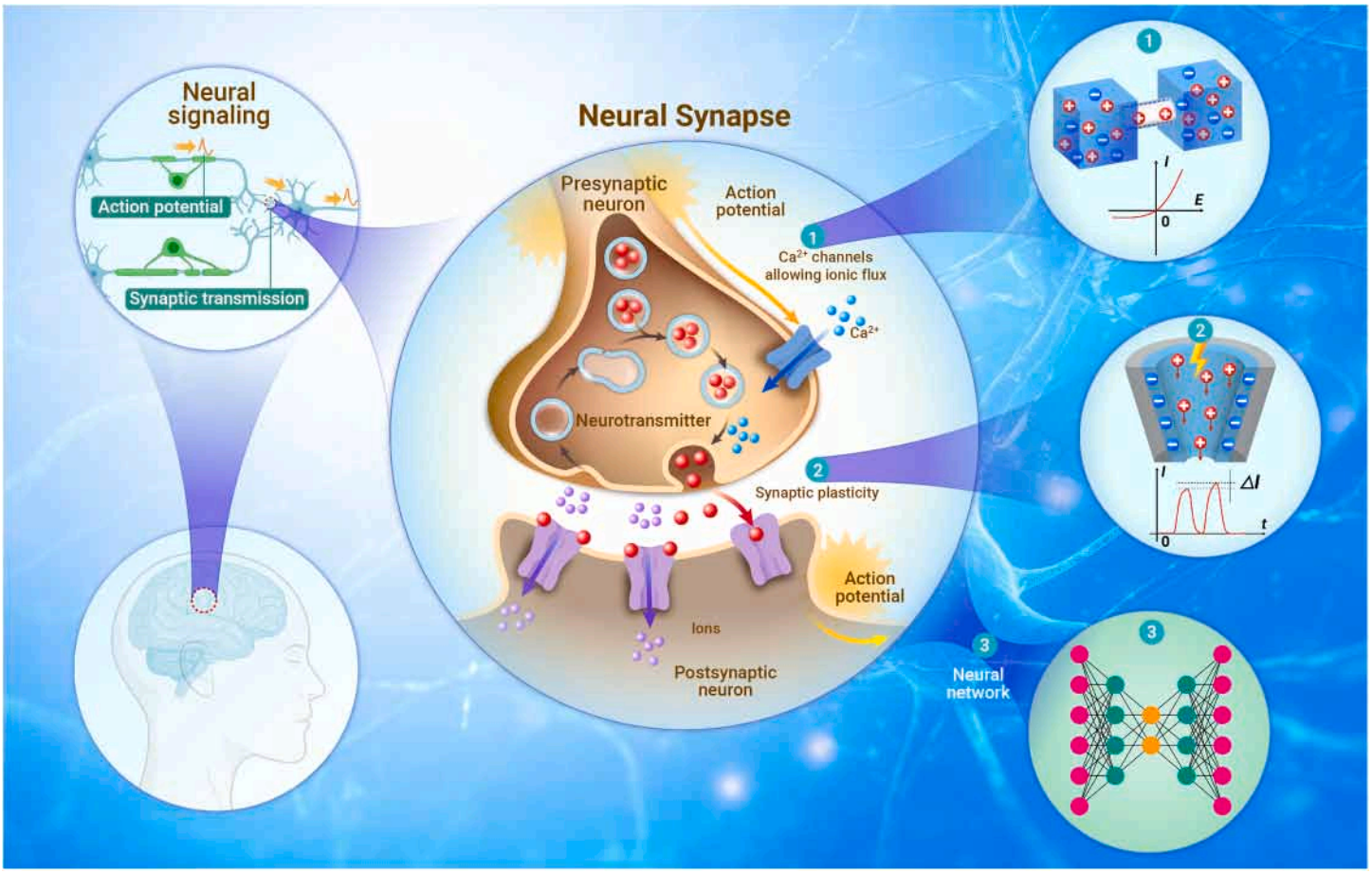


Figure 1. Hierarchically organized iontronic systems can progressively emulate the multi-level functionalities of biological synapses, thereby enabling neuromorphic intelligence

these fields drive ion redistribution, establishing ionic concentration gradients and directional interfacial potentials. Under this excitation, the EDL is transformed from a passive screening layer into an active ionic unit, enabling directional ion migration and time-dependent charge redistribution. This mechanism converts mechanical stimuli into interfacial electrostatic modulation, producing ionic flux and response without continuous power input.[5] Functionally, this process provides a physical analog of synaptic operation. The asymmetric interface defines pre- and post-synaptic-like regions, while ion migration and release driven by the asymmetric potential landscape mimic neurotransmitter dynamics, generating transient currents and residual ionic states.[6] Vesicle-fusion-like behavior is physically represented by the rapid release and redistribution of ions from interfacial EDLs, driven by triboelectric-induced polarization. This process is analogous to Ca^{2+}-triggered neurotransmitter release in biological synapses. Because the formation and relaxation of asymmetric EDLs are inherently time dependent, the system naturally supports excitation-response coupling, temporal integration, and memory effects. At the device level, such asymmetric EDLs exhibit ionic memristive behavior reminiscent of synaptic plasticity.[7] Differential ion adsorption and migration establish hysteretic EDL states evolving over multiple timescales, enabling short-term facilitation and long-term potentiation. Chemical control over ion species and hydration dynamics further tunes retention and relaxation, allowing programmable memory windows analogous to adaptive learning. Together, these processes establish a continuum from excitation to memory. Directional ion migration across asymmetric EDLs recapitulates the essential sequence of synaptic function, excitation, release, and retention within a unified interfacial framework. Thus, asymmetric EDLs serve as a minimal and interface-dominated material prototype of the synapse, in which triboelectric-induced polarization, ionic transport, and interfacial electrostatics are intrinsically coupled to enable energy-efficient neuromorphic functionality.

IONIC MEMRISTIVE NETWORKS AS PLATFORMS FOR ADAPTIVE NEUROMORPHIC LEARNING

The human brain operates as a nonlinear ionic network in which cognition emerges from the interplay of excitatory and inhibitory interactions. This behavior is governed by three coupled principles, bidirectional signaling, synaptic plasticity, and spatiotemporal integration, that transform distributed ionic motion into coordinated perception and learning. In iontronic systems, these principles are intrinsically linked: bidirectional signaling arises from oppositely directed ionic fluxes and conductance modulation, synaptic plasticity reflects the history-dependent evolution of ionic states and conductance, and spatiotemporal integration emerges from network-level processing of ionic signals. Together, they define a hierarchy from ionic transport to memory and system-level computation, which is increasingly realized in physical devices. At the device level, Janus MXene membranes with dual ion selectivity reproduce the balance between excitation and inhibition by directing counter-flowing ionic fluxes under osmotic gradients, emulating neural homeostasis.[8] Single-pore nanofluidic memristors capture synaptic plasticity through hysteretic ionic transport and reconfigurable conductance, enabling potentiation and depression behaviors.[9] When assembled into networks, these systems exhibit associative and logical learning, with synaptic weight updates governed by Hebbian-like rules. Beyond electrical signaling, iontronic systems integrate mechanical and chemical stimuli into coherent responses. Geometrically asymmetric hydrogel-based iontronics link deformation-induced ion redistribution with logic gating, enabling real-time tactile sensing and feedback reminiscent of biological mechanotransduction.[10] Together, these iontronic architectures recapitulate the hierarchical organization of neural systems, spanning balanced signaling, adaptive weight modulation, and multimodal integration. Through cooperative ion transport and dynamic interfacial coupling, ionic memristive

networks establish a physical basis for embodied intelligence, where computation emerges from the evolution of matter, energy, and charge.

FUTURE DIRECTIONS

Despite rapid advances in ionic-electronic coupling architectures, realizing embodied intelligence, where cognition emerges from the coevolution of matter, energy, and information, remains a grand challenge. Progress will hinge on three frontiers: temporal adaptability, material-algorithm coevolution, and energy-cognition integration. Future devices must achieve adaptive temporal dynamics, enabling ionic transport and polarization kinetics to evolve with feedback and environment, thereby establishing stability alongside plasticity. The next generation of neuromorphic systems should merge material dynamics with computation, allowing physical state variables such as ion concentration and local potential to function as active computational elements that learn through their own evolution. This integration remains challenging due to the need for precise control of dynamic ionic processes across multiple time- and length scales, the establishment of reliable mappings between evolving physical states and computational functions, and the maintenance of stability under strongly coupled non-equilibrium conditions. Ultimately, integrating sensing, memory, and computation into architectures where energy consumption itself guides learning may transform energy efficiency into a cognitive feature. Such convergence of ionic physics and adaptive algorithms points toward intelligent matter, systems that compute and learn through the intrinsic dynamics of charge, matter, and energy.

FUNDING AND ACKNOWLEDGMENTS

This work was supported by the China Postdoctoral Science Foundation (certificate number 2025M781041) and the National Natural Science Foundation of China (grant number 22479016).

DECLARATION OF INTERESTS

The authors declare no competing interests.

REFERENCES

1. Li, J., Zhao, W., Fu, C. et al. (2025). An ion-electronic hybrid artificial neuron with a widely tunable frequency. *Nat. Commun.* **16**:7911. DOI:10.1038/s41467-025-63195-7
2. Yang, F., Peng, P., Yan, Z.-Y. et al. (2024). Vertical iontronic energy storage based on osmotic effects and electrode redox reactions. *Nat. Energy* **9**:263–271. DOI:10.1038/s41560-023-01431-4
3. Peng, P., Shen, P., Qian, H. et al. (2025). Photochemical iontronics with multitype ionic signal transmission at single pixel for self-driven color and tridimensional vision. *Device* **3**:100574. DOI:10.1016/j.device.2024.100574
4. Liu, W., Mei, T., Cao, Z. et al. (2024). Bioinspired carbon nanotube-based nanofluidic ionic transistor with ultrahigh switching capabilities for logic circuits. *Sci. Adv.* **10**:eadj7867. DOI:10.1126/sciadv.adj7867
5. Li, X., Wei, Y., Gao, X. et al. (2025). Harnessing triboiontronic Maxwell's demon by triboelectric-induced polarization for efficient energy-information flow. *Joule* **9**:101888. DOI:10.1016/j.joule.2025.101888
6. Li, X., Amaratunga, G., Wang, Z.L. et al. (2026). Unlocking Interfacial Charge at Dielectric Solid-Liquid Interfaces via Triboelectric Nanogenerator Probe. *SmartSys* **2**:e70019. DOI:10.1002/sys3.70019
7. Xiong, T., Li, C., He, X. et al. (2023). Neuromorphic functions with a polyelectrolyte-confined fluidic memristor. *Science* **379**:156–161. DOI:10.1126/science.adc9150
8. Li, X., Wang, Z.L. and Wei, D. (2025). Iontronic logic control driven by dynamic electrical double layer regulation. *Iontronics* **1**:2. DOI:10.20517/iontronics.2025.02
9. Ling, Y., Yu, L., Guo, Z. et al. (2024). Single-Pore Nanofluidic Logic Memristor with Reconfigurable Synaptic Functions and Designable Combinations. *J. Am. Chem. Soc.* **146**:14558–14565. DOI:10.1021/jacs.4c01218
10. Ouyang, Y., Li, X., Du, Y. et al. (2025). Mechano-Driven Neuromimetic Logic Gates Established by Geometrically Asymmetric Hydrogel Iontronics. *Small* **21**:2409998. DOI:10.1002/smll.202409998