Sovereign Neuro-Evolution: A Co-Designed Framework for Auditable, Biophysically-Anchored Adaptation in Human-Digital Biospheres

Core Engine Architecture: A Rust/JavaScript Co-Design for Auditable Evolution

The technical implementation of the ota-neuromorphevolution framework is predicated on a robust, two-part architectural design that separates a high-assurance, deterministic core from a flexible, event-driven orchestrating layer . This separation ensures that all neuromorphic adjustments are subject to rigorous, auditable validation before being applied, thereby preserving user sovereignty. The architecture consists of a secure backend built in Rust, designated as the "inner-ledger," and a frontend orchestration layer implemented in JavaScript, which interacts with the host operating system and external agents . This division of labor creates a powerful synergy where the Rust core acts as the immutable engine of truth, while the JavaScript layer provides the necessary interface for scheduling, packaging proposals, and managing user feedback .

The cornerstone of this architecture is the `EvolutionFrame`, a compact, typed data structure that serves as the sole communication channel between the outer world and the inner-ledger . This frame encapsulates every proposed change to the neuromorphic system in a standardized format, preventing the exposure of raw model internals or arbitrary code execution, which are critical security and privacy vulnerabilities [6] . The `EvolutionFrame` schema is meticulously designed to represent any upgrade as a small, typed surface that can be audited, replayed, and rolled back, ensuring a transparent and safe evolution process . Its fields include essential metadata such as the `host` identity, a unique `frame_id`, the `plane` of the neuromorphic component (e.g., `SoftwareOnly`, `NeuromorphAdapter`, `OrganicCpuTile`), the `scope` of the change (e.g., `Weights`, `Routing`, `IoAdapter`), the resource `cost` in terms of FLOPs (`flop_budget`) and nanojoules (`nJ_budget`), and the expected `effect` bands for latency and error . By constraining all interactions to this single, well-defined structure, the system eliminates ambiguity and establishes a clear contract for all evolutionary proposals .

The Rust-based inner-ledger is the authoritative engine responsible for parsing, validating, and applying these frames. It operates as a sealed trait implementation, ensuring that its logic cannot be subverted by external actors . The primary responsibility of the ledger is to enforce a series of non-negotiable guard-rails that protect the host's biophysical integrity and sovereignty. These validations occur at multiple levels, creating a multi-layered defense-in-depth strategy. First, the ledger consults the current state of the host's `LifeforceBand` and `SafetyCurveWave` . If either of these is in a "HardStop" state, the evolution frame is immediately rejected with a `DenyHardStop` verdict, regardless of its other attributes . This provides an atomic-level safety mechanism against potentially harmful modifications. Second, the resource costs specified in the `EvolutionFrame` are validated against the host's token-based budgets, including `BRAIN` and `NANO` for computational complexity and structural changes, as well as the broader `EcoBandProfile` that governs environmental impact . Proposals that exceed these budgets are also denied, ensuring that neuromorphic work is treated as just another governed trait within the host's overall resource management .

The following table details the conceptual Rust schema for the `EvolutionFrame` and its associated types, which collectively form the basis of the inner-ledger's input validation.

Schema Component	Type	Description
`EvolutionPlane`	Enum	Specifies the hardware plane of the adaptation: `SoftwareOnly`, `NeuromorphAdapter`, or `OrganicCpuTile`.
`EvolutionScope`	Enum	Defines the scope of the change: `Weights`, `Routing`, `IoAdapter`, or `SchedulerHint`.
`EvolutionCost`	Struct	Contains resource budgets: `flop_budget` (computational cost), `nJ_budget` (energy cost), and `eco_intent` (environmental profile).
`ExpectedEffect`	Struct	Represents anticipated outcomes in bounded ranges: `latency_band` (i8), `error_band` (i8), and `eco_impact_band` (EcoImpactScore).
`GuardsSnapshot`	Struct	Captures the host's safety context at the moment of submission: `lifeforce_band`, `safety_wave`, and `daily_turn_seq`.
`EvolutionFrame`	Struct	The complete, typed delta for a proposed change. Includes `host`, `frame_id`, `plane`, `scope`, `cost`, `expected_effect`, and `guards_snapshot`.

Upon successful validation, the Rust engine proceeds to calculate the precise micro-adjustment, known as a `SystemAdjustmentDelta`. This is not a raw tensor or arbitrary code but a small, reversible change such as a `ScaleDelta` (a fractional change to a weight), a `WaveBudgetShift` (an adjustment to a signal frequency budget), or a `NanoEnvelopeAdjust` (a modification to a low-level parameter envelope) . This deterministic application of small, typed deltas ensures that the system evolves gradually and predictably, avoiding abrupt shifts that could cause cognitive or physiological overload . The final output of the inner-ledger is an `EvolutionDecision` object, which contains the original `frame_id`, a `verdict` (`Safe`, `Defer`, or `DenyHardStop`), and the list of `applied_deltas` if the change was approved . This structured output allows the outer layer to react appropriately to the ledger's ruling.

The JavaScript layer, typically residing in a host control-plane like "Reality.os," serves as the orchestrator and user-facing interface . Its primary function is to package candidate updates from external sources—such as an AI chatbot suggesting a filter adjustment for a navigation adapter—into a valid `EvolutionFrame` object . This layer handles the serialization of the frame into a JSON-RPC payload and communicates with the underlying Rust ledger via a defined RPC endpoint . The JavaScript client then awaits the `EvolutionDecision` from the ledger. Based on the verdict, it drives subsequent actions: applying UI or haptic feedback to the user, scheduling retries for deferred requests, or initiating rollback procedures for failed attempts . Critically, the JavaScript layer has no authority over resource allocation, consent enforcement, or safety gating; its role is purely propositional and reactive . This strict separation ensures that the ultimate decision-making power remains firmly within the high-assurance Rust core, creating a system that is both programmatically flexible and cryptographically secure . The semantic parity between the two layers, sharing the same schema and decision logic, ensures that the JS orchestrator always reflects the true state dictated by the ledger, preventing any divergence or manipulation of the core rules .

Biophysical Anchoring and Hardware Integration with Organic Neuromorphics

A defining characteristic of the ota-neuromorphevolution framework is its explicit integration with organic neuromorphic hardware, such as organic electrochemical transistors (OECTs), organic electrochemical neurons (OECNs), and electronic-circuits based on resistive memory (ECRAM) devices . The system's design philosophy treats these physical components not as autonomous controllers but as "governed organs" under the sovereign authority of the software-defined inner-ledger . This approach aligns the system's operational cadence and safety protocols with the intrinsic biophysical and electrochemical dynamics of the underlying hardware, ensuring that adaptations feel gradual and stable from a biological perspective . The choice of a 3-minute evolution interval is not arbitrary; it is deliberately set to be much longer than the millisecond-to-Hertz response times observed in organic neuromorphic devices, allowing for stable, incremental learning without inducing abrupt changes that could lead to discomfort or cognitive overload [44] [63]. This temporal decoupling is fundamental to the concept of a human-digital biosphere where technology adapts to the user, not the other way around.

The framework models the neuromorphic hardware as a collection of "adapter tiles" or "planes," each with its own distinct cost model, behavior, and set of governing traits . For instance, an `OrganicCpuTile` might have a different energy-per-operation profile compared to a simulated `SoftwareOnly` plane . This tiling abstraction allows the system to reason about resources on a per-component basis, enabling fine-grained control and optimization. Each adapter operates within a BRAIN/SUGAR-style scheduling economy, where they fire in response to specific events, draw upon a local "sugar" credit balance, and may be automatically downscaled or pruned if their long-term utility is deemed low . This event-driven, credit-based model prevents runaway adaptation and ensures efficient resource utilization. The Rust-ledger governs the rules of this internal economy—for example, determining how sugar credits are replenished from the global `LifeforceBand`—thereby maintaining system-wide stability and safety [1].

The deep integration with organic hardware extends to leveraging its unique physical properties as features of the governance system. Organic neuromorphic devices are renowned for their ultra-low power consumption, with some achieving synaptic events at energies as low as 2.08 femtojoules (fJ), comparable to the estimated energy of a single biological synapse (1–10 picojoules) [1] [2] [5]. This efficiency is directly accounted for in the `EvolutionFrame`'s `nJ_budget` field, allowing the system to enforce granular energy constraints and align with the broader `EcoBandProfile` goals . Furthermore, the hardware itself can provide the substrate for key functions. Research has demonstrated that OECTs can be used to emulate crucial biological synaptic behaviors, including excitatory post-synaptic currents (EPSC), paired-pulse facilitation (PPF), short-term plasticity (STP), and long-term plasticity (LTP) [2] [11]. One study showed that an OECT could achieve stable long-term potentiation through electropolymerization, a process that increases the gate's volumetric capacitance to permanently strengthen a synaptic connection [11] [12]. This process, while consuming approximately 30 nJ per pulse, is stable for at least two months and provides a physical mechanism for persistent adaptation [12]. The software framework would propose an evolution frame that triggers such a process, but the execution is managed by the hardware according to the physical principles of electrochemistry, not arbitrary software commands.

The bridge between the abstract software logic and the physical device behavior is a critical area of implementation. While the provided context does not specify the exact mapping, it implies a formal interface where the `SystemAdjustmentDelta` produced by the Rust ledger translates into specific electrical or electrochemical parameters for the hardware. For example, a `ScaleDelta` might correspond to adjusting the amplitude of a voltage pulse sent to an OECT's gate, while a `WaveBudgetShift` could alter the frequency of stimulation patterns used to induce plasticity [2]. The hardware, in turn, responds with its characteristic spiking dynamics or changes in conductance, feeding back into the system's state. This symbiotic relationship ensures that the neuromorphic components contribute rich, low-power sensing and adaptation while remaining subordinate to the overarching software-defined governance layer [97]. The system treats them as highly capable but ultimately governed organs, contributing to the host's function without ever gaining control over the host itself . This model is further reinforced by treating neuromorphic adapters as governed traits, whose behavior is parameterized by ALN shards (consent, eco profile, evolution budget) and enforced via sealed inner-ledger traits, making it impossible for vendors to redefine rewards or bypass guards .

Governance as Code: Embedding Neurorights and Adaptive Consent

The most profound aspect of the ota-neuromorphevolution framework is the deep, inseparable integration of governance and rights enforcement directly into the codebase, a principle referred to as "governance as code." Rather than treating neurorights as a separate policy overlay, they are encoded as non-optional, first-class constraints at the same layer as the technical implementation . This co-design approach ensures that principles of sovereignty, privacy, and autonomy are not merely aspirational but are cryptographically and logically enforced by the system itself. The framework is architected from the ground up to protect three core neurorights: Mental Privacy, Mental Integrity, and Cognitive Liberty [6] [7].

Mental Privacy is safeguarded by a strict data handling protocol that prevents the off-host transfer of raw neural data [6]. The system is designed to operate on low-dimensional, task-specific features or safety summaries computed locally on the host [6]. This aligns with Personal Neuroinformatics architectures, where sensitive high-dimensional EEG or other neural data remains confined to a user-owned store, and only processed, anonymized insights are shared [7]. This prevents risks such as 'thought eavesdropping' and brainprint tracking, where intercepted signals could reveal an individual's mental content or be used for profiling [6]. The system's very design, which only accepts `EvolutionFrame`s with defined `cost` and `expected_effect` bands, inherently limits the information exposed about the internal state of the neuromorphic network, further enhancing privacy .

Mental Integrity, defined as immunity from unwanted interference with the mind, is protected through automatic, cryptographic enforcement mechanisms [6] [7]. The `LifeforceBand` and `SafetyCurveWave` serve as the primary guardians of this right . Any proposed evolution frame that would cause the system's state to violate these bounds is rejected before it can even be considered for application. The `HardStop` and `SoftWarn` states of these bands act as an atomic-level firewall, preventing any action that could compromise the host's biophysical stability or cognitive state . This automated enforcement provides a level of protection that goes beyond simple user permission, actively preventing harmful changes from occurring.

Cognitive Liberty, the right to self-modify or enhance one's mental processes, is preserved through a sophisticated consent mechanism centered on `MetabolicConsent` and sealed traits . The user is the ultimate authority who grants or revokes consent for specific neuromorphic features, including enhancements [6]. This authority is enforced at the protocol layer, making it impossible for external agents or vendor code to delegate control away from the user . The system's architecture ensures that no adapter can change stake, legal identity, or control channels; they can only request local evolution micro-steps within the user's consent envelope . This design makes the user the sovereign owner of their own cognitive capital, a concept analogous to Tokenized Cognitive Capital (TCC), which seeks to create market frameworks for pricing and trading cognitive assets [23].

Central to this framework is the implementation of an "adaptive consent" model, inspired by practices in biobanking and genomic research [3] [90]. This moves beyond static, one-time agreements to a dynamic, living consent system that supports sustained trust and participant autonomy [8] [10]. Users can pre-approve broad classes of updates—for example, permitting the "navigation lane" to self-tune every 3 minutes within defined EcoBands and LifeforceBands—while still retaining real-time override capabilities . This creates a baseline of trust and enables a degree of automation. However, the system remains highly responsive to real-time signals. Continuous monitoring of subjective and physiological indicators (e.g., overload signals, discomfort markers) can trigger automatic downscaling or pausing of evolution without requiring further user authorization [3]. This reflects the principle of "living consent," where the user's ongoing, implicit agreement is inferred from their continued engagement and physiological stability [8]. This dynamic approach balances the convenience of continuous, adaptive updates with the immediate need for safety and control, directly addressing neurorights concerns around subconscious manipulation and behavioral steering [6] [7].

Public-Space Lane-Switches: Event-Driven Adaptation in Navigation, Safety, and Communication

The abstract principles of the ota-neuromorphevolution framework are made concrete through its application to three prioritized public-space interaction lanes: navigation, safety alerts, and communication assistance . This modular approach allows for specialized adaptation within a unified, sovereign control system, demonstrating how the host's neuromorphic biosphere can dynamically adjust to contextual demands from the environment. The core innovation is the "lane-switch," an event-driven mode change that respects the host's local sovereignty and is mediated entirely by the inner-ledger . In this model, external infrastructure, such as smart rooms or shared displays, cannot directly modulate the user's neuromorphic hardware. Instead, it emits a signed "context event" (e.g., `"navigation_lane_suggested"` or `"safety_alert_high_priority"`) that the host's system can subscribe to . This event-driven switching paradigm ensures that all interaction is initiated by the environment but controlled by the user [6].

When a host receives a signed context event from a public-space infrastructure, the on-host negotiation process begins . The JavaScript orchestrator in the host OS receives the event and passes it to the inner-ledger for evaluation. The ledger then performs a multi-faceted check to determine whether to activate the corresponding lane. This check involves consulting the current `LifeforceBand` and `EcoBandProfile` to ensure the requested mode change does not exceed the host's available biophysical and environmental budgets . Simultaneously, the system validates the request against the user's `MetabolicConsent` traits to confirm that the proposed adaptation falls within the user's pre-approved consent envelope for that specific lane . Only if all conditions are met will the host's system decide to proceed with the lane-switch.

For each lane, a specific "lane profile" defines the active neuromorphic adapters, their allocated FLOP and energy budgets for the 3-minute turn, and the types of evolution tokens permitted . This profile dictates the specific micro-adjustments that can be proposed. For example, a "Navigation Lane Profile" might permit adjustments to sensitivity bands and routing filters, while a "Safety Alert Lane Profile" might prioritize low-latency processing and allow for suppression of non-critical stimuli [100]. When a context event suggests entering a particular lane, the host maps this event to the appropriate lane profile, allocates the necessary resources from the per-turn budget, and proposes one or more `EvolutionFrame`s to the Rust ledger for approval . The user retains full control and can always override or reject the switch, ensuring that the adaptation remains a collaborative process between the user and the environment, mediated by the host's sovereign core .

This model is particularly relevant for applications like accident-aware traffic management, where V2X (Vehicle-to-Everything) technology integrates real-time accident reports and congestion data to improve safety [100]. In such a scenario, a vehicle's onboard system could receive a high-priority safety alert. The host system would evaluate this alert against its internal state and consent rules. If conditions are favorable, it might propose an evolution frame to the neuromorphic hardware to adjust tactile or auditory perception modules, boosting the priority of obstacle detection and suppressing non-critical notifications to maintain driver focus [102]. Similarly, in a complex urban environment, an AI assistant could suggest switching to a "high-focus navigation lane" to help the user navigate efficiently. The host would evaluate this request, and if approved, might propose a micro-adjustment to increase the precision of its spatial reasoning filters . Throughout this entire process, the external agent (the AI or the infrastructure) never gains direct control over the neuromorphic hardware; it only proposes a framed delta, and the host's inner-ledger decides the final course of action . This preserves the user's sovereignty by ensuring that all interaction is mediated by the host's inner-ledger, which acts as a firewall between the user's internal state and the external environment [6] .

Per-Turn Evolution and SMART Token Autonomy

The ota-neuromorphevolution framework operates on a strict, deterministic cadence of 3-minute "evolution turns," a pacing mechanism designed to ensure that neuromorphic adaptations are gradual, stable, and aligned with the slower intrinsic dynamics of organic devices . This cadence is implemented through a host-local scheduler that opens a narrow window for evolution proposals every three minutes . During this window, a bounded number of evolution tokens can be proposed, evaluated by the inner-ledger, and either committed or discarded under the watchful eyes of `Lifeforce` and `Eco` guards . This timed, batched processing model contrasts with continuous, open-ended adaptation, providing a crucial rhythm that allows the system to stabilize and the user to remain in control. The use of a fixed interval, such as 3 minutes, is a deliberate design choice to manage expectations and prevent cognitive fatigue, similar to how other systems manage user attention, such as the cost of a 3-minute phone call to the United States being a tangible unit of value [40].

Within each 3-minute turn, adaptation is expressed through SMART-like tokens, which represent discrete, micro-adjustments to neuromorphic traits . This concept borrows from the idea of using multi-agent, real-time tokens to manage real-time systems . Each neuromorphic adapter—such as a navigation module, a haptic perception filter, or a communication assistant—is treated as an autonomous agent whose ability to adapt is governed by a token budget . These tokens are not arbitrary model rewrites but are constrained by a predefined set of possible micro-adjustments, such as scaling weights, shifting budget allocations, or adjusting parameter envelopes . The total number of tokens available per turn is capped by the host's `SCALE` budget, which is itself gated by the `LifeforceBand` and daily turn sequence . This token-based economy ensures that the system's evolution is quantifiable, reversible, and explainable, matching current thinking on neurorights and dynamic autonomy [90].

The system must also incorporate safe per-turn thresholds and model scalable laws to evolve responsibly over time. Initially, conservative limits are established, such as a small maximum number of traits or adapters that can change during a single 3-minute interval . These thresholds are not static; they can be raised slowly if recent turns demonstrate stable behavior, characterized by the absence of adverse signals like cognitive overload or error spikes . This creates a feedback loop where the system's autonomy is granted incrementally based on its proven reliability. This mirrors the way neuromorphic hardware papers evaluate endurance and long-term potentiation, where performance is monitored over extended periods to validate stability [11] [44]. The scoring and pruning rules for the SMART tokens add another layer of governance. Adapters that consistently fail to improve outcomes—for instance, by generating noisy alerts or confusing suggestions—may lose their token budget over time, preserving autonomy for the more useful ones under the user's sovereign control [47]. This dynamic allocation of resources ensures that the system's adaptive capacity is focused on beneficial enhancements.

The following table outlines the key components and their roles in the per-turn evolution process:

Component	Role in Per-Turn Evolution	Governing Constraints
3-Minute Turn Timer	A host-local scheduler that opens an evolution window every 3 minutes, allowing for a bounded number of proposals.	Fixed cadence based on system stability requirements.
SMART Tokens	Represent discrete micro-adjustments (e.g., `ScaleDelta`, `WaveBudgetShift`). Each neuromorphic adapter is an agent with a token budget.	Per-turn budget caps, scoring/pruning rules based on utility.
Per-Turn Thresholds	Conservative initial limits on the number of traits/adapters that can change per turn to ensure stability.	Initial values derived from device response times and safety margins.
Scaling Laws	Rules that allow for a slow increase in per-turn thresholds if recent evolution turns show stable behavior (no overload, no adverse signals).	Stability metrics (e.g., hours/days of good performance), empirical data on user reaction.
Inner-Ledger	The Rust core that validates all proposals against `Lifeforce`, `Eco`, and `SCALE` budgets, and applies approved micro-adjustments.	Immutable, deterministic logic enforcing all safety and resource constraints.

This structured, token-based approach to autonomy provides a viable path toward creating neuromorphic systems that are both powerful and safe. By combining a rigid, human-scale temporal framework with a dynamic, utility-based token economy, the system achieves a balance between automation and control, ensuring that evolution is always a collaborative and sovereign process.

Synthesis and Future Directions: From Conceptual Design to Empirical Validation

The ota-neuromorphevolution framework presents a comprehensive and deeply integrated system for the sovereign, granular, and biophysically-grounded evolution of neuromorphic hardware. Its core strength lies in the co-design of a technical "engine" and a governance "constitution," where neurorights are not an afterthought but are embedded as first-class constraints within the codebase . The architecture, built on a Rust/JavaScript partnership, leverages the `EvolutionFrame` as a universal language for proposing and auditing all changes, ensuring a transparent and auditable evolution path . This is further solidified by integrating organic neuromorphic hardware as "governed organs," whose intrinsic properties like low power consumption and specific response dynamics inform the system's safety and pacing protocols [1] [11] . The framework's practical application is demonstrated through its implementation of event-driven, host-sovereign "lane-switches" for public-space interactions, preserving user control in dynamic environments . Finally, the use of a 3-minute turn cadence and SMART-like tokens provides a structured, manageable approach to autonomy, balancing automation with continuous user oversight .

This research establishes a foundational blueprint for a human-digital biosphere that is both interactive and sovereign. However, several areas require further investigation and empirical validation to transition from this conceptual design to a fully realized system. The first step is the formal specification of SMART tokens. Their precise format, lifecycle, and the detailed scoring and pruning logic for neuromorphic adapters must be defined . Questions remain regarding how tokens are earned, what specific criteria determine an adapter's utility, and what constitutes a failure state that leads to a reduction in its autonomy [47] .

Second, while the initial design incorporates conservative thresholds, the development of safe and effective scaling laws is a critical, long-term research endeavor . This requires gathering empirical data on how users perceive and react to varying levels of autonomy, how different combinations of active neuromorphic adapters affect overall biophysical load, and what stability metrics should trigger an increase in the system's adaptive capacity [44] . This is a complex problem in human-computer interaction that may benefit from methodologies used in clinical trial design, which aim to recruit only likely responders based on biomarkers [94] .

Third, the bridge between the abstract software logic and the physical hardware needs to be formally defined. The mapping from the `SystemAdjustmentDelta` produced by the Rust ledger to the specific electrochemical parameters of an OECT—such as gate voltage pulses, polymerization times, or ion concentrations—is a crucial engineering challenge [11] [12] . Understanding this relationship is essential for translating a software proposal into a reliable physical change in the device's synaptic weight or firing characteristics.

Finally, the user experience for managing the "living consent dashboard" is a significant hurdle . Designing an intuitive and effective interface for controlling thousands of potential evolution paths is a formidable UX challenge. Lessons from participatory research frameworks, such as Community-Based Participatory Research (CBPR), could be invaluable [8] [10] . Engaging users in co-designing these interfaces, much as patient advocates shape modern research programs, would be essential for building trust and ensuring the system remains truly under user control [3] .

In summary, the proposed framework successfully lays out a pathway toward a future where humans can interact with and augment their own cognition through neuromorphic technology without sacrificing sovereignty or safety. By grounding abstract rights in concrete Rust schemas, event-driven hardware models, and adaptive consent protocols, it offers a viable and principled approach to navigating the complexities of the human-digital frontier.

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