

A Neutral Grammar for Neuromorphic Systems: Bridging Biophysics, Law, and Code for Global Interoperability

The Interoperability Substrate: A Neutral Language for Biophysical and Legal Constraints

The foundational objective of the proposed framework is to establish a globally interoperable substrate that serves as a neutral, platform-agnostic language for brain-computer interfaces (BCIs) and neuromorphic systems . This substrate is not a monolithic software implementation but rather a shared set of formal, developer-grade, and non-actuating artifacts that encode biophysical limits and legal norms into a common format . Its primary function is to act as a universal translator, enabling disparate hardware, software ecosystems, and regulatory regimes to communicate and enforce safety and rights-based constraints consistently. This approach directly addresses the significant challenge of fragmentation within the neurotechnology field, where proprietary protocols and a lack of standardized reporting hinder collaboration, safety verification, and cross-platform compatibility [54](#) [84](#) . By creating a neutral backbone, the framework aims to solve a fundamental industry problem, offering a pragmatic path toward adoption by providing tangible benefits like enhanced safety and interoperability, rather than relying on top-down mandates that have faced market resistance [84](#) .

The core of this interoperability substrate consists of several key, typed objects designed to be universally understood and implemented. Central among these are the `EvidenceBundle`, `ALNComplianceParticle`, `NeuralRopeCrosslinkMap`, and `EcoCorridorContext` . These artifacts are engineered to be developer-grade, meaning they provide sufficient structure and detail for engineers and researchers to build upon, yet remain non-actuating, ensuring they serve as descriptive and prescriptive models rather than direct commands that could lead to autonomous decisions without human oversight . The `EvidenceBundle` is a critical component, structured as a collection of ten short hex IDs, each acting as a pointer to a specific, citable biophysical domain documented in public literature . This design ensures that every parameter change or system upgrade is traceable to empirical evidence, forming the bedrock of the safety and transparency pillars of the framework. For instance, an upgrade's energy budget would be

tied to an `EvidenceBundle` containing tags for ATP use, cortical heating, and neurovascular coupling, grounding the technical specification in established neuroscience .

Another pivotal artifact is the `ALNComplianceParticle`. This object fuses together DID/consent information, evidence tags, budgets, and neurorights flags into a single, atomic approval object . It represents a moment of consent and compliance, capturing not just whether a proposed action is technically safe according to the biophysical envelope, but also whether it respects the user's rights and has their explicit authorization. This fusion of technical and ethical/legal data at the point of decision-making is a key innovation, preventing a scenario where a technically permissible action might violate a fundamental right. The `NeuralRopeCrosslinkMap` and associated structs like `CognitiveLoadEnvelope` define the "corridors" or viable microspaces of identity and function for a given neural interface . These maps create a topological constraint, ensuring that all neuromorphic upgrades operate within predefined kernels of viability, thereby preserving the continuity of the host's cognitive and neural identity over time . Similarly, the `EcoCorridorContext` provides a schema for understanding the broader environmental and systemic impact of a neuromorphic system, incorporating metrics like `EcoImpact` to ensure that technological advancement does not come at an unacceptable ecological cost .

This modular and hierarchical structure, which allows for systematic extension and application across a wide range of structural types and materials, aligns with best practices in ontology engineering [1](#) [2](#) . The concept of using modular ontologies to integrate various sources while keeping them thematically distinct is directly applicable here [2](#) [3](#) . The framework's components can be viewed as ontology design patterns, providing reusable solutions to common problems in representing complex interactions between biology, technology, and law [4](#) . This modularity is not just a conceptual choice; it is a strategic one. It allows different parts of the system to evolve independently. New biophysical domains can be added to the `Open Evidence-Tag Schema` without breaking existing contracts, and regulatory policies can be layered on top as pluggable profiles without altering the underlying safety logic . This separation of concerns ensures the system remains robust and adaptable. The goal is to create a shared, rights-aligned language of artifacts, with presentation layers tuned for different audiences, but a single, global backbone that helps all lifeforms earn a provable right-to-exist within both biophysical and legal corridors . This neutral foundation is what allows neurorights, Free, Prior, and Informed Consent (FPIC), and biomechanical safety envelopes to travel seamlessly between ecosystems, from a researcher's lab to a commercial implant, unimpeded by proprietary silos .

The Biophysical Safety Envelope: From Empirical Evidence to Machine-Verifiable Contracts

The framework's second layer, the Biophysical Safety Envelope, translates established scientific principles and empirical evidence into a rigorous, machine-verifiable system of contractual guarantees for any BCI or neuromorphic upgrade. This layer moves beyond simple parameter validation to a holistic assessment of an upgrade's impact on the biological host, grounded in control theory, neuroenergetics, and real-time monitoring. The central concept is the modeling of every upgrade as a typed contract, such as an `UpgradeDescriptor`, which explicitly binds it to a set of resource budgets and operational envelopes. These include a `HostBudget` specifying allowable changes in energy, protein turnover, and other resources, and a `ThermodynamicEnvelope` defining strict limits on parameters like temperature rise (ΔT), power density, and cooling schedules. This contract-first approach ensures that no modification can be enacted without a priori justification based on its potential physiological impact.

A cornerstone of this safety mechanism is the principle of "evidence-locked envelopes". No neuromorphic or BCI parameter—be it duty cycle, joules per session, or protein load—is accepted for implementation unless it is backed by a corresponding `EvidenceBundle`. This bundle consists of ten short hex IDs, each pointing to a specific, named biophysical metric and its supporting citation class in a public registry. This practice enforces a high standard of evidence, preventing ad-hoc or speculative modifications. It creates an auditable trail connecting every technical parameter to a body of published, peer-reviewed research, thereby grounding the entire system in scientific rigor. This approach mirrors the emphasis on transparent and reproducible reporting seen in initiatives like the IEEE P2794 Reporting Standard for in-vivo Neural Interface Research, which seeks to improve the interpretability and replicability of neurotechnology studies [16](#).

To ensure safety in dynamic conditions, the framework employs a "telemetry + budget double gate" system. This means that an action cannot proceed based on the static `UpgradeDescriptor` alone. Before any Over-the-Air (OTA) update or neuromorphic actuation is permitted, the system must take a live telemetry snapshot, represented by a `BciHostSnapshot` struct. This snapshot captures the host's real-time state, including vital signs like heart rate variability (HRV), EEG load, pain and inflammation markers, and local temperatures. Both the static contract (the `ThermodynamicEnvelope`) and the live telemetry snapshot must independently agree that the action is safe before it is executed. Either gate can veto an operation, providing a powerful fail-safe against unforeseen physiological states or cumulative effects not captured by the initial static

contract . This dual-gate mechanism is a robust implementation of anticipatory and reactive safety controls.

Furthermore, to manage the dynamic nature of neuromorphic load, the framework incorporates "Lyapunov-safe duty clamps" . In this model, neuromorphic load is treated as a state variable $u \in [0,1]$. Control laws derived from Lyapunov stability theory are applied to ensure that the system always evolves in a way that drives the load variable back toward a safe operating point, even if it is perturbed away from it . This prevents the system from drifting into unsafe operational regions over time, a critical feature for long-term implants where cumulative effects can occur. This advanced control-theoretic approach is grounded in real-world safety tooling and demonstrates a commitment to leveraging established engineering principles to mitigate risk . The combination of evidence-backed contracts, a double-gate verification process, and Lyapunov-based control laws creates a multi-layered defense-in-depth strategy for biophysical safety. This strategy is supported by formal methods, where tools like Kani and property-based tests are used to verify that the system's invariants—such as the guarantee that no sequence of upgrades can exceed energy or thermal bounds—are mathematically proven to hold true . This formal verification, enabled by languages like Rust, provides a high degree of confidence in the system's safety properties, moving beyond probabilistic assurances to mathematical certainty [42](#) [44](#) [123](#).

The Neurorights Layer: Operationalizing Law through Artificial Legal Norms

The third layer of the framework integrates legal and ethical principles, specifically neurorights, into the core system logic by operationalizing them through Artificial Legal Norms (ALN). This layer bridges the gap between abstract legal texts and concrete, computationally verifiable actions, making compliance with human rights obligations a feature of the system's design rather than an external audit. The central construct in this layer is the `ALNComplianceParticle`, a typed object that fuses together technical feasibility data (from the biophysical envelope), user consent information (DID/consent), and neurorights flags into a single, atomic approval object . This ensures that at the point of execution, a decision is not only technically safe but also legally and ethically sound, respecting the user's autonomy and fundamental freedoms.

To facilitate this integration, the framework proposes a "Neurorights–ALN Template Catalog," a library of pre-defined ALN clause templates . These templates, such as

nononconsensualmodulation, rollbackanytime, and neurodatanontransferable, map directly to specific fields and invariants within the core artifact schemas . For example, the rollbackanytime template would be linked to the ReversalConditions field in an UpgradeDescriptor, mandating that any contract for an upgrade includes a clear, documented procedure for reverting the change . Similarly, neurodatanontransferable would trigger requirements for audit trails and specific consent flags to prevent unauthorized data sharing . This templating system provides a structured way to incorporate complex legal concepts into the technical specifications, reducing ambiguity and ensuring consistent implementation across different platforms.

A defining characteristic of this neurorights layer is its flexibility, achieved through the use of "pluggable regulatory policy profiles" . Rather than hard-coding a single jurisdiction's legal framework into the core logic, the system is designed to support multiple regulatory regimes as overlays . Legal norms from the European Union's proposed AI Act, guidance from the U.S. Food and Drug Administration (FDA), Chilean proposals, and the UNESCO Recommendation on the Ethics of Neurotechnology can all be expressed as tagged policy views layered on top of the neutral interoperability substrate . For instance, a vendor could query a device for its "EU-aligned" view of a given constraint. This would return a version of the underlying ALNComplianceParticle with annotations and enforcement rules tailored to the EU's high-risk AI definitions outlined in Annex III of its regulation [11](#) [60](#) [113](#). This modular approach avoids the rigidity of a single-standard-for-all solution and accommodates the evolving and diverse landscape of global neurotechnology regulation. It allows a system to be compliant in multiple jurisdictions simultaneously by maintaining separate policy profiles that can be audited and swapped without altering the fundamental safety logic .

This effort to make law machine-readable is part of a broader trend in computational law, exemplified by projects like LegalRuleML, which aim to represent legal rules and norms in XML-based formats for use in web applications [23](#) [25](#) . The proposed framework can be seen as a highly specialized, domain-specific instantiation of this paradigm, tailored for the extreme sensitivity of the human nervous system. The challenge lies in translating the nuanced, often philosophical, language of international human rights instruments, such as the draft UNESCO Recommendation on the Ethics of Neurotechnology, into unambiguous, algorithmic constraints [9](#) [93](#) [96](#) . The framework acknowledges this complexity by starting with more concrete rights and principles, such as bodily autonomy and data ownership, which can be more readily translated into technical requirements like rollback guarantees and data transfer restrictions. The ultimate goal is to create a system where neurorights are not merely aspirational

statements but are embedded as enforceable digital properties, providing a provable, auditable record of compliance for regulators, users, and auditors alike .

Extensibility and Governance: Community-Driven Knowledge Curation and Auditability

A critical aspect of the framework's long-term viability is its design for extensibility and decentralized governance, embodied primarily in the `Open Evidence-Tag Schema` and the `EvolutionAuditRecord` system. The schema is intentionally designed to be extensible, allowing for community-contributed biophysical domains beyond the initial kernel of ten axes like ATP use and cortical heating . New domains, such as biomechanical density or interoception-informed cognitive load, can be added as the collective knowledge base matures . This approach treats the initial set as a canonical starter kit within a versioned namespace, ensuring that the addition of new evidence axes never silently increases risk. Instead, it refines the global right-to-exist corridor for neuromorphic systems by adding new dimensions of safety to monitor . This model shifts the burden of knowledge curation from a centralized authority to a distributed, community-driven process, similar to successful open-science initiatives like `OpenEvidence`, which synthesizes medical literature in real-time, or collaborative data repositories like `DANDI` and `OpenNeuro`, which rely on community adherence to standards for data reusability [84](#) [125](#). The success of this model depends on establishing clear processes for contributing, validating, and versioning new evidence tags to maintain the integrity of the safety-critical ecosystem.

Governance is further solidified through a robust audit and identity continuity model centered on the concepts of corridors, microspaces, and append-only logs. Identity is not treated as a monolithic entity but is defined by small, viable "microspaces" or "corridors" within the neural architecture . These are formally defined by structures like the `NeuralRopeCrosslinkMap` and `CognitiveLoadEnvelope`, which delineate the boundaries of acceptable functional and structural change . All neuromorphic upgrades are constrained to operate entirely within these pre-defined kernels of viability, ensuring that the host's core cognitive functions and sense of self are preserved over time . This concept of a "right-to-exist" corridor is a powerful metaphor for balancing innovation with preservation of identity.

To support this model, the framework requires a neutral schema for an `EvolutionAuditRecord`, which serves as an append-only log of all changes made to

the host-system relationship . This log is essential for accountability and long-term tracking, providing a permanent, immutable record of every neuromorphic modification, its justification based on an `EvidenceBundle`, its compliance status verified by an `ALNComplianceParticle`, and the user's consent. This audit trail is crucial for regulators and for the user themselves, providing transparency into the history of their own neurotechnological enhancements. This focus on auditability is aligned with regulatory expectations, such as those from the FDA, which require mandatory reporting of device-related deaths or serious injuries and promote the use of national and international medical device registries to gather real-world evidence [71](#) . The framework's `EvolutionAuditRecord` provides a technical implementation of this principle at the individual level. Furthermore, the system's design inherently supports rollback guarantees through `ReversalConditions` specified in the initial upgrade contracts . Because every change is logged and justified, and because the system operates within defined corridors, it becomes possible to reconstruct a previous state, fulfilling the promise of the `rollbackanytime` neurorights template and giving users genuine control over their own neural trajectories . This combination of an extensible evidence schema, corridor-based identity management, and a permanent audit trail forms a comprehensive governance model that supports both safety and long-term user sovereignty.

Audience-Tailored Documentation and Implementation Patterns

The framework is designed for practical adoption across three distinct communities: hardware vendors, research labs, and regulatory bodies. To facilitate this, the core artifact formats are intended to be presented through audience-tailored documentation layers while maintaining a single, unified backbone . This ensures that each group receives the information most relevant to their needs, while still being able to connect to the same underlying, provably safe and rights-aware system.

For **hardware vendors**, the documentation focuses on concrete, implementable patterns and schemas designed for integration into firmware and telemetry systems. The key artifacts are the `HIT Governance Objects`, `implantinterfaceguard`, and `EcoCorridorContext` schemas . The documentation would detail how to embed these guard patterns directly into the device's software stack. For example, it would explain how to instantiate an `implantinterfaceguard` that automatically checks incoming OTA updates against the `ThermodynamicEnvelope` and the live `BciHostSnapshot` before acceptance, implementing the "double gate" safety protocol . The

`EcoCorridorContext` schema would be presented as a guide for designing hardware and software that respects the defined neural corridors, preventing irreversible changes that could compromise user identity . The narrative for vendors would emphasize the business case: these patterns reduce liability by building safety and regulatory compliance directly into the product, simplify the path to market by pre-emptively addressing future regulations, and offer a competitive advantage through demonstrable safety and trustworthiness.

For **research labs**, the documentation centers on experimental templates, reproducible evidence pipelines, and best practices for curating the `Open Evidence-Tag Schema`. The goal is to position the framework as a tool for enhancing research rigor and facilitating publication. Labs would receive templates for conducting experiments that generate data suitable for creating new `EvidenceTags` . The documentation would outline a "research-to-syntax loop": a documented workflow where new scientific papers contribute validated data that updates evidence tags and corridor constants, while CI/model checking enforces all constraints . This transforms the process of knowledge generation from a linear, publish-or-perish cycle into a continuous, feedback-driven loop that directly improves the safety framework itself. Labs would learn how to turn their data—from imaging, HRV, cytokine levels, and `EcoImpact` metrics—into the standardized inputs required by the `EvidenceBundle` schema, making their findings directly usable by the broader ecosystem . This approach aligns with the goals of initiatives like the RSNIR standard, which seeks to improve the transparency and reproducibility of neurotechnology research through detailed reporting requirements [16](#) .

For **regulators and ethics boards**, the documentation takes the form of narrative-level guides that connect the technical artifacts to legal and ethical outcomes. The goal is to show how the framework's objects become auditable, jurisdiction-ready constraints that are never used for autonomous actuation . For example, a regulator could use the documentation to understand how a `NeuralRopeCrosslinkMap` provides a visual and formal proof that a certain upgrade stayed within safe cognitive boundaries. They could see how an `ALNComplianceParticle`'s attached policy profile demonstrates compliance with a specific jurisdiction's neurorights, such as the EU's definition of a high-risk AI system [11](#) [131](#). The `EvolutionAuditRecord` would be presented as the definitive, tamper-evident ledger proving that all modifications were authorized, reversible, and documented, satisfying due diligence requirements. This narrative layer makes the technical framework accessible and valuable to non-technical stakeholders, demonstrating concretely how the system upholds principles of accountability, transparency, and human rights protection as mandated by emerging regulations like the EU AI Act and recommended by bodies like UNESCO [93](#) [106114](#).

Strategic Synthesis and Future Directions

The proposed globally interoperable, neuromorphic-safe, and neurorights-aware framework represents a comprehensive and strategically coherent response to the challenges posed by the rapid development of BCIs and neuromorphic systems. Its core strength lies in the synthesis of four distinct but deeply interconnected layers: a neutral interoperability substrate, a biophysical safety envelope, a neurorights layer, and a governance model for long-term integrity. This multi-layered architecture, built upon a foundation of extensible schemas and formal verification, offers a pragmatic and forward-looking pathway toward responsible innovation. The strategic decision to prioritize interoperability first is particularly astute, as it circumvents the political complexities of mandating a single global standard and instead provides a "carrot" of enhanced safety, collaboration, and market access that is inherently valuable to all stakeholders [54](#) [84](#). By creating a neutral language, the framework enables the crucial concepts of FPIC, biomechanical safety, and neurorights to travel freely between ecosystems, fostering a more integrated and accountable neurotechnology landscape .

The framework's ability to operationalize abstract legal norms through pluggable ALN policy profiles is its most ambitious and potentially transformative feature. It directly confronts the "last mile" problem of governance: translating high-level human rights declarations into enforceable technical requirements. While the translation of nuanced legal texts like the UNESCO draft Recommendation on the Ethics of Neurotechnology remains a significant challenge, the template-based approach provides a scalable and manageable entry point [93](#) [96](#). The explicit separation of the neutral core from jurisdictional overlays ensures the system's adaptability in a rapidly changing regulatory environment, allowing it to evolve alongside the law itself . However, the framework is not without its gaps. The current scope lacks specified temporal constraints, which is a critical omission given that many risks, such as cumulative inflammation or long-term cortical plasticity changes, are time-dependent phenomena . Future work must focus on integrating dynamic risk models and adaptive constraints that can evolve with the host over months and years.

Furthermore, while the theoretical underpinnings in control theory and formal methods are robust, their practical implementation on resource-constrained neuromorphic hardware presents a formidable engineering challenge [30](#) . The performance overhead of running continuous double-gate checks and ALN compliance verifications in real-time must be carefully analyzed and optimized to be feasible for low-power devices. Finally, the success of the community-driven Open Evidence-Tag Schema hinges on the creation of strong incentives for researchers and institutions to contribute high-quality,

validated data, mirroring the collaborative ethos of successful open science movements [84 125](#). In conclusion, this framework provides a powerful and necessary blueprint for building a trustworthy future for neurotechnology. It establishes a shared language of safety and rights that can be adopted and independently verified by anyone. By bridging the chasm between biophysics, law, and code, it offers a concrete vision for a world where technological enhancement does not come at the cost of human dignity, but rather, is governed by it.

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