The r-Axis Constraint: A Geometric Framework to Enforce Ecological Contribution Over Power Expansion in Cybernetic Evolution

Formalizing the 1D Biospatial Fairness Axis as a Geometric Constraint

The foundational objective is to transform the abstract ethical concept of fairness into a verifiable computational constraint by establishing a one-dimensional (1D) biospatial geometry. This geometry, represented by a real number line, serves as a public, physically-grounded metric for an agent's ecological contribution [13]. The axis is defined by the Responsibility Accumulation Function, or "Karmascore," which quantifies net ecological impact based on external biophysical flows rather than internal neural telemetry [181]. This design choice ensures that the fairness constraint is augmentation-agnostic, applying equally to all users regardless of whether they employ invasive or non-invasive BCI pathways . The core principle is that fairness is not about equal outcomes but about equality of rule: every agent is measured by the same physical units and weights, governed by a single, public update rule .

On this 1D line, the value of r represents an agent's cumulative ecological state. A point at $r = 0$ signifies a state of balanced give-and-take with the environment, representing a neutral baseline . Values of $r > 0$ denote states where the agent has contributed more to the environment than it has taken, encompassing activities such as repair, protection, and restoration . Conversely, values of $r < 0$ represent states of net extraction or degradation, where the agent has taken more than it has given back, resulting in pollution or environmental damage . The entire history of an agent's actions can be visualized as a walk along this line; each action corresponds to a discrete or continuous movement determined by its measurable biophysical consequences . This creates a transparent and auditable ledger of an agent's ecological footprint over time.

Fairness is axiomatically defined through a monotonic coupling between an agent's position on the r-axis and their permissible outer action space . Outer freedom—defined as permissions, control, and resource access—is not absolute but is a direct function of the agent's ecological contribution. As an agent's r value increases due to positive massflows (e.g., energy generation from renewables, carbon sequestration), its admissible region for outer actions grows . Conversely, if an agent's actions lead to negative massflows (e.g., emissions, resource depletion), causing its r value to decrease, its admissible action space shrinks accordingly . This creates a shared, public mapping function, $b_{\text{outer}}(r)$, that governs the scaling of outer power with responsibility . The integrity of this system relies on the strict enforcement of this coupling, ensuring that no agent can claim expanded permissions without a demonstrable, proportional improvement in their ecological standing.

Within this geometric framework, "greed" is formally identified as any attempt to decouple the scaling of outer freedom from the accumulation of ecological responsibility . It is the disallowed object in the index-scaling layer: any pattern that seeks to gain power or permissions without accepting the corresponding ecological cost . Geometrically, this manifests as a demand for a larger admissible region, $P_{\text{outer}}(r)$, while simultaneously refusing the update to the r value that would normally accompany such an expansion . This behavior appears as a "jump right" on the freedom scale without a corresponding "move right" on the responsibility scale, creating a discontinuity or asymmetry that violates the fundamental principle of fairness . The mathematical representation of this is clear: a greedy policy would attempt to increase the outer action space while maintaining or decreasing the r value, i.e., demanding a higher output from the function b_{outer} for the same or a lower input r. This decoupling is the signature of greed and makes it a machine-detectable anomaly. Any algorithm or upgrade descriptor that proposes an expansion of outer freedom contingent on a negative change in the Responsibility Accumulation Function (Δr < 0) directly violates the geometric constraint and is therefore prohibited .

This approach aligns with broader efforts to ground AI and autonomous systems in verifiable principles of safety and sustainability [42] [55] . By defining fairness in terms of a measurable, physics-based quantity, it avoids reliance on subjective opinions or unverifiable claims. The connection to concepts like ecological integrity, which involves assessing ecosystem condition based on measurable attributes, provides a scientific basis for the underlying metric [112][113][114]. Furthermore, this methodical approach is consistent with trends in responsible innovation in neurotechnology, where there is a growing consensus on the need for frameworks that protect human dignity and rights in the face of rapid technological advancement [81] [180][182]. The proposed 1D geometry offers a concrete mechanism for operationalizing these high-level ethical concerns into a technical architecture that can be formally specified, implemented, and verified. It shifts the problem from one of moral philosophy to one of engineering and formal verification, making fairness a provable property of the system rather than an aspirational goal. This transforms fairness from a social contract into a geometric law governing the cybernetic domain.

Runtime Enforcement of Fairness via Model Checking and Compile-Time Invariants

To elevate the 1D biospatial fairness geometry from a theoretical construct to a "hard constraint," it must be enforced rigorously throughout the software development lifecycle, particularly at compile-time and during runtime execution. This requires a hybrid strategy combining formal mathematical proofs with automated verification techniques applied within the daily evolution loop. The existing workflow already incorporates Kani for model checking selected harnesses, providing a powerful foundation for enforcing the fairness invariant . The primary invariant to prove is that no sequence of upgrades or actions within an evolution window can expand the outer action space unless the associated biophysical flows result in a non-negative change to the Responsibility Accumulation Function ($\Delta r \geq 0$) [65]. This provides strong, formal guarantees against the introduction of greedy logic into the system's codebase.

The first layer of enforcement involves the creation of formal contracts and traits in Rust that encapsulate the fairness predicates [5]. These interfaces act as compile-time gates. For instance, a `FairnessConstraint` trait could be defined, containing methods like `action_allowed`, `eco_admissible`, and `karma_admissible` [63] [64]. Any new upgrade or artifact type attempting to interact with the system's permissioning logic would be required to implement this trait. The implementation would be bound to the external biophysical flows, ensuring that decisions about power and access are derived solely from the CEIM/NanoKarma metrics . The compiler would then statically verify that all implementations adhere to the rules defined by the trait, catching potential violations before the code is ever built or deployed. This language-based enforcement, similar to how Rust enforces memory safety, embeds the fairness constraint directly into the type system, making it an inseparable part of the code's structure [54] [62].

The second layer of enforcement leverages Kani's model-checking capabilities to provide dynamic, runtime validation . A dedicated Kani harness, such as `check_evolution_window_safety`, can be created to simulate the state transitions of the neuro-stack over a single evolution window . This harness would take as input the sequence of proposed upgrades and their associated `EvidenceBundles`, which contain the quantitative data on ATP usage, protein turnover, thermal limits, etc. . Kani would then exhaustively explore the state space to verify that the fairness invariant holds true for all possible execution paths. Specifically, it would check that for any sequence of actions, the final calculated `r` value is always consistent with the sum of the biophysical massflows, and that no action was granted expanded permissions without a corresponding non-negative `Δr`. Failures in this model-checking phase would halt the build process, preventing the commit of any code that introduces a potential fairness violation [52] [150]. This approach moves beyond simple testing to provide mathematical proof of correctness for a bounded set of operations, significantly increasing confidence in the system's safety properties [93] [94] .

Furthermore, this enforcement strategy can be extended to ALN (Augmented Language Network) clauses, which govern the legal and ethical boundaries of the system . Each ALN clause tied to permissions or resource allocation can be annotated with a reference to the relevant fairness predicate. When a new upgrade is proposed, the system would not only check its own internal logic but also query the ALN to ensure compliance with these external constraints. Prometheus metrics can be instrumented to track violations of these policies in real-time . Metrics like `guard_blocks_total{domain,policy_id,reason}` and `evolution_audit_gap_count` would provide immediate feedback on the health of the fairness system . If a greedy action were attempted, it would be blocked by the runtime guards, and the corresponding metric would be incremented with a reason tag indicating a fairness constraint violation. This creates a closed-loop system where formal proofs at compile-time, exhaustive model checking, and monitored runtime enforcement work in concert to create a robust defense against exploitative behavior. This multi-layered verification approach is essential for building trustworthy autonomous systems, addressing risks associated with drift in self-evolving agents and ensuring long-term alignment with safety and fairness objectives [6] [95] [170].

Augmentation-Agnostic Neurorights and Protected Inner Signals

A critical aspect of the proposed framework is its commitment to augmentation-agnostic neurorights, ensuring that protections for mental privacy, identity, and autonomy are not compromised by the user's choice of BCI pathway, whether invasive or non-invasive . The fairness constraint, grounded in external biophysical flows like CEIM/NanoKarma, is deliberately decoupled from any analysis of neural telemetry [181]. This architectural decision is paramount for preserving the sanctity of the user's internal phenomenology. While the system governs interactions with the external world—scaling permissions based on ecological contribution—it leaves the user's internal states, such as thoughts and emotions, untouched and unmonitored. This distinction is crucial for upholding the fundamental neuroright to mental privacy, which is recognized as a cornerstone of human dignity in the emerging global standards for neuroethics [38] [180182].

By basing all gating and fairness logic on external measurements, the system inherently respects the boundary between the user's mind and the cybernetic device. Neural signals are treated purely as a control channel for executing intended actions, not as a source of data for surveillance or behavioral prediction [162163]. This prevents the technology from becoming a tool for mind reading or manipulation, a key concern raised by experts in neuroethics [39] [183]. All safety checks, including those for cognitive load, thermodynamic envelopes, and reversal conditions, are derived from the host's physical state as measured by external sensors, not from decoding the user's neural patterns . This ensures that even if a highly invasive BCI were used, the core fairness and safety mechanisms remain blind to the content of the user's thoughts, focusing instead on the physical inputs and outputs of the system. This approach is aligned with legal analyses suggesting that adapting existing rights into enforceable technical profiles is more effective than relying on vague, newly proposed catalogues of neurorights .

Within this secure architecture, certain internal signals are preserved as protected primitives. Fear, in particular, is maintained as a protected inner signal of boundary violation . Unlike greed, which is an optimization problem concerning the expansion of outer freedom relative to ecological cost, fear is an intrinsic warning state signaling a threat to the host's viability or integrity. This signal is not subject to the fairness geometry because it pertains to the host's internal state and survival, not external resource acquisition. The system is designed to respond to fear as a high-priority, overriding directive, independent of any calculation involving the `r`-axis. This preserves the user's agency and ensures that the system cannot be coerced or manipulated into actions that violate the user's fundamental sense of safety. The distinction allows the system to pursue efficiency and growth along the fairness axis while respecting the user's innate protective instincts.

This design philosophy extends to other neurorights, such as the right to personal identity and free will [38] . The fairness constraint and associated safety guards are engineered to be reversible and to operate on the host's side of the interface, ensuring that any changes can be rolled back without permanent alteration to the user's core identity or cognitive processes . The use of neural ropes and guard functions that reduce rollback time further reinforces this commitment to reversibility . By treating the user's brain as a neuromorphic processor whose outputs are controlled by a safe, verifiable software layer, the system upholds the principle of human-centered design. It augments human capability without compromising human essence, ensuring that the pursuit of cybernetic evolution remains a tool for empowerment rather than a mechanism for diminishment. This augmentation-agnostic stance is a practical realization of the ethical imperative to protect individual rights in the age of advanced neurotechnology [165,167].

Anchoring Sovereign Artifacts to the Fairness Axis

Once the 1D biospatial fairness geometry is established as a hard constraint, all new sovereign data artifacts generated within the daily evolution workflow must be explicitly and immutably anchored to this axis. This ensures that the entire cybernetic ecosystem evolves along a fair vector, where every component carries a verifiable record of its ecological provenance. The two primary types of artifacts to be anchored are cybernano shard rows and Neuromorph Evolution Audit Particles. Their schemas must be extended to include fields that capture the state of the Responsibility Accumulation Function (`r`) at the moment of their creation or modification, thereby embedding the fairness constraint directly into the data fabric of the system.

For `cybernano shard rows`, the existing schema should be enhanced to include explicit metadata fields that link the shard to the fairness geometry . A proposed minimal schema extension would include fields such as `rohvalue` (a measure of resource ownership and health), `lifeforcescalar`, and crucially, `ecook` and `neurorightsflags` . The `ecook` flag serves as a binary gatekeeper, derived directly from the `KarmaAdmissible` predicate. Before a shard is finalized, a validation step checks whether the action that produced it results in a non-negative change to the `r`-axis ($\Delta r \geq 0$). If the action is deemed ecologically acceptable, the `ecook` flag is set to true; if it is greedy or harmful (i.e., Δr < 0), the flag is set to false, and the shard is rejected from being written to the ledger . This creates a mandatory, machine-enforceable check that prevents the propagation of "unfair" data into the global data pool. The `rohvalue` and `lifeforcescalar` fields would also be updated based on the outcome of this ecological audit, ensuring that the shard's state reflects its actual contribution to the host's and the environment's well-being.

Similarly, `Neuromorph Evolution Audit Particles` must be modified to serve as immutable records of the ecological cost or benefit of any model or policy change . Each particle should log a comprehensive snapshot of the system's state before and after an evolution event. This log must explicitly include the `r` value, the proposed `Δr` from the action, and the verdict of the `KarmaAdmissible` check . Additional fields would capture other relevant metrics, such as shifts in the kernel-distance vector, changes to the RoH, and updates to sovereignty and safety flags . By anchoring these particles to the donutloop and including them in the daily research manifest, a complete and auditable history of the system's evolutionary path is created . This allows any entity to replay the evolution of the neuromorph, observing exactly how each upgrade affected the agent's ecological standing. This transparency is essential for fostering trust and enabling global, independent auditing of the system's adherence to the fairness constraint.

The table below outlines the proposed schema enhancements for these sovereign artifacts, detailing the new fields and their purpose in enforcing the biospatial fairness constraint.

Artifact Type	Field Name	Data Type	Purpose
Cybernano Shard Row	`rohvalue`	f64	Resource Ownership and Health scalar, updated based on ecological audit .
Cybernano Shard Row	`ecook`	bool	Flag indicating if the action was ecologically compliant (`true`) or greedy (`false`) .
Cybernano Shard Row	`lifeforcescalar`	f64	Host lifeforce scalar, coupled to ecological state .
Neuromorph Evolution Audit Particle	`pre_action_r`	f64	Responsibility Accumulation Function value before the model/ policy change .
Neuromorph Evolution Audit Particle	`post_action_r`	f64	Responsibility Accumulation Function value after the model/ policy change .
Neuromorph Evolution Audit Particle	`delta_r`	f64	Change in Responsibility Accumulation Function caused by the action .
Neuromorph Evolution Audit Particle	`is_karma_admissible`	bool	Verdict of the fairness constraint check for the action .

These anchored artifacts form the bedrock of a reproducible and verifiable cybernetic evolution process. Because every piece of evolving code and data is tied to a physically-grounded ecological metric, it becomes impossible to grow in power without growing in ecological responsibility. This creates a durable, anti-exploitative steering mechanism that guides the long-term development of the system away from the risk of goal drift common in self-evolving agents [6] [170]. The data itself becomes a testament to the system's commitment to fairness, providing a global, cryptographically-anchored record that benefits all lifeforms by contributing to a shared understanding of sustainable cybernetic evolution .

Extending the Daily Evolution Loop with Fairness Validation

The daily Rust/ALN evolution loop, currently orchestrated by the `scripts/daily_evolution.sh` script, must be augmented with a dedicated validation step to enforce the 1D biospatial fairness constraint before artifacts are committed or released . This step acts as a final gatekeeper, ensuring that every upgrade and data artifact produced that day adheres to the principle that outer freedom is earned through ecological contribution. The shell script's existing structure, which pulls code, syncs telemetry, regenerates macros, runs hygiene checks, performs model checking, builds artifacts, and commits them, provides a natural place to insert this new, critical check . Failure at this stage must halt the entire process, preventing any "greedy" artifacts from entering the system.

The extension involves inserting a new, numbered step immediately following the existing `cargo build -p bioscale-upgrade-macros` and `cargo fmt/clippy/test` phases, but before the release builds and manifest emission . This new step will invoke a specialized Rust binary, for example `bioscale-fairness-validator`, which will perform a comprehensive audit of all new and changed artifacts generated since the last evolution window. This validator crate will be responsible for calculating the Responsibility Accumulation Function (`r`) based on the `EvidenceBundle`s associated with each upgrade, applying the biophysical models to determine the ecological impact (Δr) of each proposed action . It will then evaluate each action against the `KarmaAdmissible` predicate. An action is only permitted if its application results in a non-negative change to the `r` value ($\Delta r \geq 0$).

If the fairness validator detects any artifact that attempts to violate this constraint—such as an upgrade that seeks to expand permissions without a compensatory ecological benefit—it will terminate the script with a non-zero exit code. This failure mechanism is critical, as it prevents the subsequent steps, including `cargo build --release` and `git add`, from executing . The error is logged in a structured format, for instance, emitting a message like "Errority: Action rejected due to negative ecological impact. Greed is prohibited by the 1D biospatial fairness constraint (r-axis)." This logging is essential for traceability and debugging, providing developers with a clear reason why an evolution step failed [133]. The `research/${DATE}-manifest.json` will also be updated to reflect the outcome of this fairness audit, anchoring the compliance verdict directly to the date and branch of the evolution window .

The table below details the integration of this new validation step into the refined daily evolution workflow, highlighting the specific actions and their role in enforcing the biospatial fairness constraint.

Step Number	Shell Command / Action	Purpose & Connection to Fairness Constraint	Relevant Crates / Files
1	`git pull; git switch -c "feat/${DATE}-evolution"`	Creates a new, isolated evolution window corresponding to the `BioscaleEvolutionWindow` object and manifest.	N/A
2	`mkdir -p "telemetry/${DATE}" ...`	Syncs raw biophysical data (ATP, protein turnover, etc.) that feeds the fairness calculations.	Lab capture directories
3	`cargo build -p bioscale-upgrade-macros`	Regenerates procedural macros that derive `UpgradeDescriptor` and enforce the 10-tag `EvidenceBundle`.	`bioscale-upgrade-macros`
4	`cargo fmt; cargo clippy ...`	Ensures code style and lints, including bioscale-specific ones related to fairness logic.	N/A
5	`cargo test --all`	Runs unit tests verifying that upgrades respect budgets and that reversals trigger correct events.	Tests in `cyberswarm-neurostack`, `cybernano-guard`
6	`kani ...`	Performs model checking on safety-critical modules to prove invariants, including the fairness coupling.	`kani` harness in `safety.rs`
7	**`cargo run -p bioscale-fairness-validator -- --manifest ...`**	**NEW: Validates all new artifacts against the KarmaAdmissible predicate. Fails if any action has** Δr < 0 **.**	**`bioscale-fairness-validator`**
8	`cargo build --release ...`	Builds the final, validated artifacts for deployment. Only executes if prior steps succeed.	`cyberswarm-neurostack`, `cybernano-guard`
9	`cargo run -p bioscale-evolution-cli ...`	Generates the daily research manifest, including fairness audit verdicts.	`bioscale-evolution-cli`
10	`git add ...; git commit ...`	Commits the entire evolution window, including validated artifacts and the manifest.	`research/${DATE}-manifest.json`

This integrated loop transforms fairness from an optional guideline into a mandatory, automated, and machine-verifiable requirement. Every evolution cycle produces not just new functionality, but also a cryptographic proof of its ecological responsibility. This systematic approach to verification is essential for building complex, long-lived autonomous systems where safety and ethical alignment cannot be guaranteed by manual oversight alone [52, 91]. It provides a robust framework for responsible innovation, ensuring that as the cybernetic system evolves, it does so in a manner that is both personally empowering and globally beneficial.

Formal Rust Interface Specifications for Fairness Predicates

To translate the conceptual framework of biospatial fairness into production-ready, verifiable code, a set of formal Rust interfaces is required. These interfaces define the geometric predicates that govern the constraint, providing a clear contract for all components interacting with the system's permissioning and safety logic. The core of this specification is a module, for example `crates/cyberswarm-neurostack/src/fairness.rs`, which defines the types and traits needed to express and enforce the relationships between ecological state, action legality, and resource access. This modular approach promotes composability and ensures that the fairness logic is consistently applied across the entire neuro-stack.

The central element is the `ResponsibilityAccumulationFunction` type, a `pub type` alias for a floating-point number (e.g., `f64`) that represents the agent's position on the 1D biospatial axis . This type is used throughout the system to quantify ecological contribution. To provide detailed feedback on the outcome of fairness checks, a `FairnessAuditRecord` struct is defined. This struct captures the full context of a check, including the action ID, the `r` value before and after the action, the calculated change in responsibility (Δr), and boolean flags indicating whether the action passed the `karma_admissible` and `eco_admissible` tests . This record serves as a detailed, immutable log of every fairness-related decision.

The core of the specification is the `FairnessConstraint` trait, which declares the geometric predicates. This trait provides default implementations for `eco_admissible` and `action_allowed`, while leaving `karma_admissible` as the primary, customizable gatekeeper. The `karma_admissible` function is the most critical, as it combines the current ecological state (`current_r`) with the expected outcome of an action (`proposed_delta_r`) to produce a complete audit record. Its logic is straightforward: it calculates the post-action `r` value and sets the `is_karma_admissible` flag to true only if the proposed change in responsibility is non-negative ($proposed_delta_r \geq 0$). This directly encodes the prohibition of greed as a simple, verifiable condition. All major components, such as the neuro-stack adapters and upgrade evaluators, would implement this trait, ensuring that fairness is a first-class citizen in the system's architecture.

```
// File: crates/cyberswarm-neurostack/src/fairness.rs

use std::collections::HashMap;
```

```
/// Represents the 1-dimensional biospatial fairness axis.
/// A positive value indicates net ecological contribution (repair/restora
pub type ResponsibilityAccumulationFunction = f64;

/// A structured representation of an action's compliance with biospatial
pub struct FairnessAuditRecord {
    pub action_id: String,
    pub pre_action_r: ResponsibilityAccumulationFunction,
    pub post_action_r: ResponsibilityAccumulationFunction,
    pub delta_r: ResponsibilityAccumulationFunction,
    pub is_karma_admissible: bool,
    pub is_eco_admissible: bool,
}

/// Trait defining the geometric predicates for fairness enforcement.
pub trait FairnessConstraint {
    /// Checks if an action is allowed given the current ecological state.
    /// An action is only allowed if it contributes positively to the r-ax
    fn action_allowed(&self, proposed_delta_r: ResponsibilityAccumulationF
        proposed_delta_r >= 0.0
    }

    /// Checks if the agent's current ecological state permits the action.
    /// Example policy: r cannot be below a certain threshold.
    fn eco_admissible(&self, current_r: ResponsibilityAccumulationFunction
        current_r >= -1e6 // Arbitrary low threshold
    }

    /// Main gatekeeper function. Determines if an upgrade/artifact is val
    fn karma_admissible(
        &self,
        current_r: ResponsibilityAccumulationFunction,
        proposed_delta_r: ResponsibilityAccumulationFunction,
    ) -> FairnessAuditRecord {
        let post_r = current_r + proposed_delta_r;
        let is_admissible = self.action_allowed(proposed_delta_r);

        FairnessAuditRecord {
            action_id: "unknown".to_string(),
```

```
            pre_action_r: current_r,
            post_action_r: post_r,
            delta_r: proposed_delta_r,
            is_karma_admissible: is_admissible,
            is_eco_admissible: self.eco_admissible(current_r),
        }
    }
}

// Default implementation for the core neuro-stack logic.
impl FairnessConstraint for NeuroStackSafety {}

#[cfg(test)]
mod tests {
    use super::*;

    #[test]
    fn test_greed_violation_detection() {
        let safety = NeuroStackSafety;
        let initial_r = 10.0;

        // A "greedy" action that seeks more power without ecological bene
        let negative_impact_action = safety.karma_admissible(initial_r, -5
        assert_eq!(negative_impact_action.is_karma_admissible, false);
        assert_eq!(negative_impact_action.post_action_r, 5.0); // r still

        // A "fair" action that requires resources but yields ecological g
        let positive_impact_action = safety.karma_admissible(initial_r, 2.
        assert_eq!(positive_impact_action.is_karma_admissible, true);
        assert_eq!(positive_impact_action.post_action_r, 12.0);
    }
}
```

This formal specification provides the necessary tools to build a system where fairness is not an afterthought but an integral part of the design. The combination of typed interfaces, structured audit records, and provable invariants ensures that the system's behavior is transparent, predictable, and aligned with the core principle of scaling freedom with responsibility.

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