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From Mis-Tags to Macro-Guardrails: A Practical Blueprint for Compiling Safety into BCI-HCI Designs

Architecting Safety at the Core: Structurally Enforcing K/S/R and Neurorights in DCMs

The foundational strategy for mitigating risks from mis-tagged domains and incomplete validators begins with the data structures themselves—specifically, the Data Collection Manifests (DCMs) and Human-Computer Interaction (HCI) profiles that define every research operation. These artifacts represent the primary contract between an autonomous agent's intent and the physical or virtual boundaries it is permitted to operate within . The current vulnerability lies in treating metadata like Knowledge (K), Safety (S), Risk (R), and neurorights classifications as optional or easily overlooked fields. To counter this, the proposed approach elevates these attributes from mere data points to integral, non-negotiable components of the struct's type definition. This is achieved by leveraging Rust's powerful type system to create a structural barrier against invalid or incomplete configurations before they can ever be processed by any downstream logic. By making K/S/R bands, privacy levels, jurisdiction rules, and neurorights tags intrinsic properties of the DCM's type, we shift the burden of proof from runtime checks to compile-time guarantees, thereby hardening the entire safety envelope.

A primary mechanism for this structural hardening is the adoption of strongly-typed wrappers for K/S/R values. Instead of representing these metrics as generic primitives like `f64` or `u8`, they should be encapsulated in dedicated struct types, such as `KnowledgeScore`, `SafetyLevel`, and `RiskBand`. This practice offers several critical advantages. First, it prevents accidental mixing of values; a function expecting a `RiskBand` cannot mistakenly be passed a `KnowledgeScore`, catching a class of bugs at compile time. Second, it allows for the embedding of validation logic directly within the wrapper's implementation. For instance, the constructor for `RiskBand` could be private, and validation logic can be attached to each type, ensuring that a `RiskBand` value is always within a predefined enum of acceptable bands [3]. Third, it provides a natural place to attach methods related to the specific metric, such as `is_within_ceiling()` for a `RiskBand` or `requires_review()` for a high `KnowledgeScore`. This

transforms simple numbers into intelligent objects that carry their own constraints and behaviors. While the provided context does not detail a specific schema for these enums, common patterns in systems managing risk involve defining discrete tiers (e.g., Low, Medium, High) rather than continuous floating-point values, which aligns well with Rust's `enum` construct.

Beyond typed fields, a more advanced technique involves encoding domain-specific constraints, particularly neurorights tags, at the type level using sealed traits and const generics. This represents the pinnacle of compile-time enforcement, moving beyond simple field presence checks to verifying logical consistency. The core idea is to define a trait that acts as a marker, such as `trait HasNeuroRightsTag;`, and then create distinct, uninstantiable structs for each valid tag, e.g., `struct NeuroRightsTag_AcceptableUse; impl HasNeuroRightsTag for NeuroRightsTag_AcceptableUse {}`. Then, a DCM struct can be made generic over this constraint: `struct DCM<T: HasNeuroRightsTag> { /<em> fields </em>/ }`. This creates a unique type for every combination of DCM data and its associated neurorights tag. Consequently, the compiler will reject any attempt to instantiate a `DCM` without providing a valid tag, preventing invalid or missing tags from ever reaching the validator layer [10]. While this approach introduces significant syntactic overhead and requires careful macro usage to manage boilerplate, it provides an unparalleled guarantee of correctness. For example, a macro could be created to simplify the generation of these types and their corresponding trait implementations, abstracting away the complexity from the end-user while retaining the safety benefits [10]. Another method for type-level strings involves creating recursive data structures to represent string literals, which can then be used as type parameters to achieve similar effects [10].

The following table outlines a comparison of different approaches to structuring DCMs with K/S/R and neurorights metadata, highlighting their respective strengths and weaknesses in the context of compile-time enforcement.

Approach	Description	Compile-Time Guarantee	Complexity	Key Rust Feature
Untagged Primitives	K/S/R and tags are stored as standard data types (e.g., `f64`, `String`). Validation is performed via runtime functions.	None. Vulnerable to mis-tagging and human error.	Low. Simple and straightforward.	Basic Struct Definition
Strongly-Typed Wrappers	K/S/R are wrapped in structs (e.g., `RiskBand(u8)`). Tags can be represented as an `enum`.	Prevents mixing of metric types. Wrapper logic can enforce value ranges.	Moderate. Requires writing wrapper types and their implementations.	Structs, Enums, Private Constructors
Type-Level Tagging	Neurorights tags are encoded as empty structs implemented for a sealed trait. DCM is generic over this trait.	Highest. Compiler enforces the existence and validity of a tag at instantiation. Prevents invalid states entirely.	High. Involves advanced concepts like sealed traits and const generics.	Sealed Traits, Generics, Const Generics
Procedural Macro Guardrail	A macro inspects the struct definition at compile time and emits a `compile_error!` if required fields are missing.	Verifies structural completeness of the definition itself. Does not validate field contents.	Moderate. Requires learning the `proc_macro` API but provides high value.	Procedural Macros

This multi-layered structural approach ensures that any artifact deemed "valid" by the compiler has already passed a rigorous set of checks. It directly addresses the user's goal of mitigating mis-tagged domains by making the correct tagging an immutable property of the artifact's type. The subsequent sections will detail how this structured data is consumed and validated by logic embedded within Rust policy crates, forming a complete, enforceable governance loop.

Codifying Governance: Implementing Composable Validator Logic in Policy Crates

While structurally enforcing metadata through Rust types forms the first line of defense, the second and equally critical line of defense is the implementation of robust, composable, and reusable validation logic. This logic serves as the engine of governance, translating high-level rules about XR-Grid zoning, jurisdictional laws, and neurorights ceilings into executable code that scrutinizes every DCM and HCI profile before an action is permitted. According to the research goal, Rust policy crates, such as `cyconetics-bci-policy`, are the designated home for this logic, providing a centralized and auditable source of truth for all safety and compliance checks . The objective is to move beyond simplistic, monolithic validation functions towards a modular architecture where individual checks are small, focused, and can be combined in various ways to suit the specific requirements of different operational contexts, such as a particular XR-Grid zone.

This approach enhances maintainability, testability, and the ability to adapt to new policies without rewriting core application logic.

The cornerstone of this architecture is the **Validator Pattern**, adapted for modern Rust. Instead of a single function returning a boolean, a dedicated `Validator` struct is introduced to orchestrate the validation process. This struct would hold a collection of accumulated errors. Individual validation methods, such as `check_electrical_limits()`, `verify_privacy_compliance()`, and `is_device_permitted_in_jurisdiction()`, would be designed to return a boolean indicating success or failure. If a check fails, the method appends a descriptive message to the `Validator`'s internal error list and returns `false`, allowing other checks to proceed [3]. This "all-or-nothing" reporting style is crucial because it provides a comprehensive audit trail of why a manifest was rejected, rather than failing prematurely on the first encountered issue. Once all checks are complete, the `Validator`'s final `Error()` method can return the full list of failures, enabling the system to provide detailed feedback to the researcher or agent. This pattern is highly composable; a `Validate()` method on the main `DCM` or `HCIProfile` struct would simply instantiate a `Validator`, call its methods to perform all necessary checks, and then return the accumulated error report [3]. An alternative to boolean-returning methods is to have them return an `Option<Error>` or a custom result type, which simplifies the calling code by eliminating the need to explicitly check a boolean and then handle the error separately [3].

To further enhance modularity, these validation functions should be organized into distinct modules within the policy crate, grouped by their domain of concern (e.g., `electrical.rs`, `privacy.rs`, `jurisdiction.rs`). Each module would expose a set of public functions that perform a specific category of checks. The higher-level validation logic in the core application would then compose these modules together. For example, a function like `fn validate_against_zone(dcm: &DCM, zone_policy: &ZonePolicy) -> ValidationResult` could be defined, which takes both the DCM to be validated and the policy rules for a specific XR-Grid zone . Inside this function, the code would iterate through the list of validators specified in the `zone_policy` and apply them to the `dcm`. This decouples the core application from the specifics of the policies, which can be updated dynamically. XR-Grid zoning, which defines hazard levels, allowed devices, and consent modes, provides the "sharp target" for these validators . The policy crate would contain the logic that interprets the zone schema and maps it to a specific set of validators to be executed. This dynamic application of rules based on context is essential for a flexible and secure system.

The following table describes key validator functions and the rules they would enforce, illustrating how abstract governance concepts are translated into concrete Rust logic.

Validator Function	Purpose	Rules Enforced	Example Inputs
`fn validate_electrical_limits(electrode_data: &ElectrodeData, limits: &DeviceLimits) -> bool`	Ensures electrical stimulation parameters are within safe bounds.	Checks voltage, current, charge density, and pulse duration against device-specific and neurorights-defined maximums.	`electrode_data`: Current applied to electrode; `limits`: Max voltage from device spec.
`fn validate_privacy_level(data_collection: &DataCollectionSpec, required_privacy: PrivacyLevel) -> bool`	Confirms that the data being collected meets the minimum privacy standards for the operation.	Verifies that sensitive data (e.g., raw EEG signals potentially linked to biological state) is not collected unless a higher privacy mode is enabled.	`data_collection`: Specification of data types to be recorded; `required_privacy`: `HighPrivacy` for certain zones.
`fn can_use_device_in_zone(device_id: &DeviceId, zone_policy: &ZonePolicy) -> bool`	Determines if a specific BCI device is permitted to operate within the given XR-Grid zone.	Consults a list of approved device IDs stored within the `zone_policy` to grant or deny access.	`device_id`: Unique identifier of the BCI headset; `zone_policy`: Defines 'approved_devices' list.
`fn is_jurisdiction_compliant(subject_did: &DID, zone_jurisdiction: &Jurisdiction) -> bool`	Validates that the user (identified by DID) is subject to the legal jurisdiction governing the XR-Grid zone.	Compares the user's domicile or residency information (linked to their DID) against the zone's accepted jurisdictions.	`subject_did`: Decentralized Identifier of the user; `zone_jurisdiction`: EU law applies in this zone.
`fn risk_band_complies_with_zone(risk_score: &RiskBand, zone_threshold: &RiskBand) -> bool`	Compares the operation's risk score against the maximum allowed risk for the current zone.	Ensures the operation's R score is less than or equal to the R ceiling defined for the XR-Grid zone.	`risk_score`: R=0.4 from the DCM; `zone_threshold`: R<=0.3 for 'high_security' zone.

By codifying these rules into a library of composable functions within a dedicated policy crate, the system transforms abstract governance principles into a tangible, machine-enforceable contract. This directly addresses the risk of "incomplete validators" by promoting a modular design where each rule is its own unit of logic, easy to write, test, and verify independently. The next section will explore how procedural macros can be used to push some of this logic even earlier, into the compilation phase, to catch errors before the program is even run.

Proactive Defense: Leveraging Procedural Macros for Compile-Time Guardrails

While runtime validation is essential for enforcing complex, contextual rules, a significant portion of the risk from mis-tagged domains can be preemptively eliminated at compile time. Procedural macros in Rust offer a uniquely powerful mechanism for this purpose, allowing developers to write code that inspects and operates on the Rust Abstract Syntax Tree (AST) during the build process [25]. This capability enables the creation of bespoke "guardrails" that can analyze DCM and HCI profile definitions before they are ever compiled into a binary, failing the build immediately upon detecting common or critical violations. This proactive defense strategy directly targets the user's goal of strengthening compile-time enforcement by turning potential runtime errors into guaranteed compile-time failures, drastically reducing the cognitive load on developers and improving the overall reliability of the system.

The most direct application of this technique is to create a procedural macro, for instance `#[enforce_manifest_validity]`, that can be applied to any struct intended to serve as a DCM or HCI profile. When the compiler encounters this attribute, it executes the macro's logic. The macro's primary task would be to inspect the structure of the annotated struct. Using the `syn` crate, it can parse the input `TokenStream` to extract the struct's definition [24] [25]. Within this definition, the macro can programmatically verify the presence and type of required fields, such as `risk_band`, `knowledge_score`, and the field containing the neurorights tag. If any of these mandatory fields are absent, the macro can generate and emit a `compile_error!` invocation [6] [25]. This causes the compiler to halt the build process and report a custom error message. The precision of this error is paramount; thanks to the `Span` information available for each token in the AST, the generated error can point directly to the line in the source code where the violation occurred, making debugging trivial for the developer [25]. This single mechanism alone would effectively eliminate the risk of accidentally submitting a manifest with a missing risk score.

Beyond simple field presence, procedural macros can enforce more sophisticated constraints. For example, a macro could be designed to validate that a `RiskBand` field's value conforms to a predefined set of acceptable enums, or that a neurorights tag corresponds to a known, valid tag defined elsewhere in the codebase. This goes beyond what is possible with basic struct definitions. Furthermore, macros can be used to enforce relationships between different parts of the system. A hypothetical macro `#[assert_risk_below(zone = "high_security")]` could be applied to a DCM struct. At compile time, this macro would look up the maximum allowed `R` score for the

"high_security" zone from a predefined policy map (which could itself be generated by another macro) and then verify that the R value in the annotated DCM does not exceed this threshold. If the check fails, the macro panics or emits a `compile_error!`, preventing the unsafe configuration from ever compiling [25]. This creates a tight coupling between the manifest's content and the external policy environment, with the check happening automatically as part of the standard build process.

The implementation of these macros relies on several key features of Rust's macro system. Function-like procedural macros, which have a signature of `(TokenStream) -> TokenStream`, are ideal for this use case as they can completely transform the item they are applied to, or, more commonly, produce a stream of tokens that replaces the macro invocation [25]. The `proc_macro` crate provides the necessary tools to work with `TokenStream`, which is a sequence of lexical tokens representing Rust code [25]. By analyzing this stream, a macro can understand the structure of a `struct`, the names and types of its fields, and even the values of constant expressions. The following table summarizes the capabilities of procedural macros in this context:

Capability	Description	Benefit	Implementation Tool
Field Presence Check	Inspect a struct definition to ensure required fields (e.g., `risk_band`, `neurorights_tag`) are present.	Prevents manifests from being compiled with missing critical metadata.	`syn::parse2` to parse the struct, then iterate over fields.
Type Validation	Verify that fields have the correct, pre-defined types (e.g., `RiskBand`, `KnowledgeScore`).	Prevents incorrect data types from being assigned to metadata fields.	Use `field.ty` from the parsed struct definition.
Value Constraint	Check that constant values (e.g., a `RiskBand` enum variant) are within an allowed set.	Prevents the use of invalid or undefined risk bands.	Compare the literal value from the parsed code against a hardcoded list.
Cross-Reference Validation	Look up policy data (e.g., zone risk thresholds) and compare it against manifest values.	Ensures manifests comply with external policy constraints at compile time.	Access external data via build scripts or generated modules.
Precise Error Reporting	Generate `compile_error!` messages annotated with `Span` information pointing to the exact source location.	Provides clear, actionable feedback to developers, speeding up debugging.	Use the `span()` method on tokens when constructing the error message.

It is important to note that procedural macros are not a replacement for runtime validation but a complement to it. They excel at checking structural and syntactic correctness, whereas runtime validators are better suited for checking semantic and contextual correctness (e.g., whether a device ID is in a list, which may change dynamically). However, by pushing as many checks as possible into the compile step, the system becomes significantly more robust. Developers receive immediate feedback, the CI pipeline can fail builds reliably, and the surface area for runtime bugs is reduced. The development effort for writing these macros is a worthwhile investment, as it yields long-

term gains in safety, reliability, and developer productivity. The integration of these macros into the standard build process of crates like `cyconetics-bci-core` provides a tangible and immediate improvement in the project's safety posture.

Integrated Safeguards: The Role of CI/CD and Automated Testing

While compile-time enforcement through Rust's type system and procedural macros provides a formidable first line of defense, a truly robust safety framework requires a multi-layered approach that extends into the Continuous Integration and Continuous Deployment (CI/CD) pipeline. The CI/CD stage acts as a crucial second line of defense, automating checks that are either too complex for procedural macros to perform or serve as an independent verification layer to ensure the integrity of the entire build artifact. This integrated safeguard model combines strict build configurations, custom validation scripts, and automated testing to create a comprehensive system that systematically rejects unsafe or non-compliant changes before they can reach production environments. This aligns with the user's emphasis on near-term implementation steps and leveraging existing toolchains like GitHub Actions to enforce governance rules automatically [26].

One of the simplest yet most effective measures is to configure the build environment to treat compiler warnings as errors. This can be accomplished by setting the `RUSTFLAGS` environment variable to `"-D warnings"` in the CI job configuration [33]. This single setting compels the compiler to fail the build if any linting rules are triggered. Lints, especially those from community lints or clippy, often catch subtle code smells, potential bugs, and deviations from best practices. By failing the build on warnings, the team enforces a higher standard of code quality and encourages developers to address potential issues proactively rather than letting them accumulate. This practice complements the work of procedural macros by focusing on the quality and clarity of the code itself, not just its structure.

Beyond standard build flags, the CI pipeline can be enhanced with custom scripts that perform additional validation. For instance, after the initial compilation succeeds, a script can be added to parse the source code or the generated artifacts to perform checks that procedural macros might miss. A script written in a language like Python or even another Rust binary could use the `syn` crate to programmatically parse all DCM definitions in the codebase and verify they conform to the expected schema. This could include checks that are parameterized by the current policy state, which might not be feasible within a

macro's execution context. Another powerful technique is the generation of Static Analysis Results Interchange Format (SARIF) files [5]. Custom validation scripts can output their findings in SARIF format, which is a standardized format for code scanning results. This allows the findings to be seamlessly integrated into IDEs, pull request comments, and security dashboards, providing a unified view of the project's health and security posture across different tools [5].

The role of automated testing is also central to this integrated safeguards model. Unit tests for the individual validator functions are essential to ensure they behave as expected under a wide range of inputs. These tests should cover both successful validation cases and edge cases that should trigger a failure. More importantly, however, are the integration tests that simulate the interaction between the various components of the system. An integration test might create a mock XR-Grid zone with specific policies (e.g., a low-risk threshold), instantiate a DCM with a slightly higher risk score, and then invoke the `validate_against_zone` function to confirm that it correctly rejects the manifest. Such tests provide a high degree of confidence that the entire chain of logic—from the struct definition, through the procedural macro guardrails, to the runtime validators—is functioning cohesively. The provided context notes that tests in a .NET application on GitHub Actions can fail due to external dependencies, highlighting the importance of designing tests that are isolated and reliable [26]. Similarly, tests for the Cybernetic Cookbook framework must be carefully architected to be deterministic and not rely on volatile external state.

The following table summarizes the roles and benefits of each component in the integrated safeguards model.

Component	Role in Safeguarding	Key Implementation Detail	Associated Risks/Mitigations
Compiler Warnings	Enforces high code quality and catches subtle bugs early.	Set `RUSTFLAGS="-D warnings"` in the CI environment.	May break the build on legitimate, non-critical warnings; requires tuning of lint rules.
Custom CI Scripts	Performs complex, semantic checks beyond the scope of procedural macros.	Parses source code or artifacts to validate against schemas or policy data.	Script complexity can introduce its own bugs; must be well-tested.
SARIF Generation	Standardizes the reporting of analysis results across tools.	Custom scripts output findings in the SARIF format for ingestion by security scanners.	Requires understanding of the SARIF specification.
Unit Tests	Validates the correctness of individual, small units of logic (e.g., a single validator function).	Write tests for all branches of logic, including error paths.	Can become brittle and slow if not maintained properly.
Integration Tests	Verifies that different system components work together as expected.	Simulate interactions, e.g., validating a DCM against a policy from a mock XR-Grid zone.	Can be complex to set up and may require test doubles or mocks.

Ultimately, no single mechanism is sufficient on its own. The true strength of the system comes from the synergy between these layers. A developer writes a DCM struct. Their IDE, powered by rust-analyzer, may provide real-time feedback. The procedural macro runs at compile time, rejecting any struct that is malformed or violates basic constraints. The CI pipeline then builds the project, failing immediately if there are any warnings. Finally, the automated test suite runs, simulating the operational context and verifying that the DCM is correctly rejected by the runtime validator when it exceeds the policy threshold. This multi-stage, redundant system of checks dramatically reduces the probability of an unsafe or non-compliant configuration ever being deployed, providing a strong technical foundation for governed autonomy.

Strategic Synthesis and Implementation Roadmap

The comprehensive analysis of the research goal reveals a clear and actionable strategy for hardening the Cybernetic Cookbook framework against the high-impact failure modes of mis-tagged domains and incomplete validators. The recommended approach is not to seek a single silver-bullet solution but to construct a multi-layered defense system that leverages the unique strengths of Rust's ecosystem. This strategy prioritizes near-term, implementable solutions within the `cyconetics-bci-core` and `cyconetics-bci-policy` crates, focusing on concrete mechanisms that embed governance directly into the codebase rather than relying on abstract discussions or manual processes . The synthesis of the findings points toward a phased implementation roadmap that delivers incremental value while building towards a more robust, compile-time-safe architecture.

The core of this strategy rests on three pillars: 1. **Structural Hardening:** Making K/S/R and neurorights metadata inseparable, required parts of the DCM and HCI profile data structures through the use of strongly-typed wrappers and, where appropriate, advanced type-level constraints. 2. **Logic Enforcement:** Codifying governance rules into a library of composable, modular validator functions within policy crates, which can be dynamically applied based on contextual information like XR-Grid zone policies. 3. **Proactive Compilation Guardrails:** Utilizing procedural macros to perform static analysis on manifest definitions at compile time, failing builds for common errors like missing tags or invalid values, and providing precise, actionable feedback.

These pillars work in concert. Structural hardening ensures that the data is well-formed. Logic enforcement provides the reasoning engine to interpret that data against complex rules. And procedural macros act as a vigilant gatekeeper at the earliest possible stage of

the development lifecycle. This integrated model directly addresses the identified risks by transforming governance from a soft, easily bypassed constraint into a hard, machine-enforced property of the software itself.

Based on this synthesis, the following phased implementation roadmap is recommended for immediate adoption:

Phase 1: Foundational Structuring and Runtime Validation (Immediate Impact) The first priority is to establish a solid foundation of well-defined data structures and a baseline set of runtime validators.

- **Action:** Refactor the DCM and HCI profile structs in `cyconetics-bci-core` to use strongly-typed wrappers for K/S/R fields (e.g., `pub risk_band: RiskBand`) instead of primitive types. Ensure all required metadata fields are non-optional.
- **Action:** Implement the `Validator` pattern as described, creating a `Validator` struct that can accumulate multiple error messages [3].
- **Action:** Begin populating the `cyconetics-bci-policy` crate with a suite of small, focused validator functions that check for electrical limits, privacy levels, and basic jurisdictional compliance . Implement a function like `validate_against_zone` that orchestrates these checks against a provided policy context.
- **Benefit:** This phase delivers immediate improvements in code clarity, maintainability, and runtime safety. It establishes a clear separation of concerns between data definition and business logic.

Phase 2: Automating Checks with Procedural Macros (Compile-Time Enforcement) With a stable foundation in place, the next step is to introduce compile-time guardrails to catch errors before the code is even run.

- **Action:** Develop a procedural macro, for example `#[validate_manifest]`, that inspects DCM structs at compile time. Its initial version should focus on a single, high-value check: verifying the presence of all required fields (K/S/R, neurorights tag).
- **Action:** Configure the CI pipeline to run this macro as part of the standard build process. Ensure that any emitted `compile_error!` will cause the CI job to fail [25].
- **Action:** Enhance the macro to leverage `Span` information to provide precise error locations in the source code, improving the developer experience [25].
- **Benefit:** This phase provides a powerful incentive for developers to adhere to the manifest schema, as violations are caught instantly with clear feedback, reducing the number of failed CI runs and speeding up the development cycle.

Phase 3: Expanding Guardrails and Strengthening the Pipeline (Advanced Automation) Once the basic macro is proven, the system can be expanded to enforce more complex rules and integrate more deeply with the CI/CD infrastructure.

- **Action:** Extend the procedural macro to perform more sophisticated checks, such as comparing a manifest's `R` score against a threshold derived from the active XR-Grid zone policy.
- **Action:** Update the CI pipeline to enforce stricter quality gates, such as setting `RUSTFLAGS="-D warnings"` to fail builds on any linting issues [33].
- **Action:** Introduce custom CI scripts that generate SARIF files for any custom validation checks, providing a standardized way to report findings to security and monitoring tools [5].
- **Benefit:** This phase moves the system closer to the ultimate goal of compile-time safety, minimizing the possibility of runtime errors due to configuration issues and establishing a mature, automated quality assurance process.

In conclusion, the path forward is clear and pragmatic. By systematically applying Rust's powerful type system, procedural macro capabilities, and robust CI/CD tooling, the project can directly mitigate the risks of mis-tagged domains and incomplete validators. This approach provides immediate, tangible benefits through improved code quality and automated checks, while laying the groundwork for a future where safety and governance are enforced by the compiler itself.

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