The Three Dividends:

Governance, Protocol, and Architecture Economics in Protocol-Governed Systems

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Abstract

This paper analyzes the lifecycle, complexity, and implementation economics of protocol-governed architecture. Building on the structural taxonomy (Paper 3) [Bachi, 2026c], governance mechanics (Paper 4) [Bachi, 2026d], deterministic enforcement (Paper 6) [Bachi, 2026f], and mutation bounding (Paper 7) [Bachi, 2026g], we model how constitutional separation affects long-term system evolution, incremental domain implementation cost, and human cognitive scaling.

We define three complementary economic properties. The **Governance Dividend** is the reduction in structural entropy, maintenance volatility, and behavioral drift achieved through explicit behavioral law and bounded mutation surfaces — operating at the organizational and lifecycle level. The **Protocol Dividend** is the reduction in marginal domain implementation cost achieved by separating governance from execution — operating at the implementation level. The **Architecture Dividend** is the structural reduction of human cognitive load achieved by relocating behavioral complexity from application code into governed protocol artifacts — operating at the human and team level. Together, they constitute the complete economic case for protocol governance.

We contrast integration-dense architectures, whose effective interaction surfaces grow superlinearly with capability count, with protocol-governed architectures whose interaction surfaces are bounded by a finite concern vocabulary, yielding linear growth in declared composition rather than emergent coupling. The paper presents the **technical debt inversion thesis**: protocol governance shifts cost from implicit runtime complexity to explicit constitutional design, inverting the technical debt accumulation curve.

We then analyze **implementation cost topology** — showing that traditional domain software conflates governance, execution, state mutation, orchestration, and integration into a single imperative codebase where integration density is the dominant cost driver. PGS restructures domain implementation into fixed, amortized, and variable layers. We formalize this as a cost topology transformation and show that the Protocol Dividend arises from the elimination of integration as an imperative code concern — not from faster coding, but from the structural relocation of orchestration, data flow, and error routing into declarative governance artifacts.

We further analyze **cognitive cost topology** — showing that the Architecture Dividend arises from the structural relocation of behavioral authority from human working memory to governance artifacts, yielding bounded per-engineer cognitive load as system size grows.

We validate all three models empirically through a greenfield domain (AI Agent Governance) that required zero engine modifications, zero custom code, and zero novel capability transforms — demonstrating that marginal domain cost approaches governance authoring effort alone.

Categories: Software Engineering (cs.SE), Software Economics, Software Maintenance

Keywords: complexity scaling, governance dividend, protocol dividend, architecture dividend, cognitive load, technical debt, lifecycle economics, implementation cost topology, integration elimination, amortization, marginal domain cost, sustainable software

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1. Position in the Series

Paper 8 established that security emerges structurally from vocabulary-bounded architecture [Bachi, 2026h].

Paper 9 examines a different question:

> *How does constitutional governance affect system complexity, implementation cost, cognitive load, and lifecycle economics?*

This paper shifts from structural invariants to economic consequences — organizational, implementational, and cognitive. Where previous papers established what protocol governance is and what properties it guarantees, this paper examines what it costs, what it eliminates, and what it returns.

The relationship is complementary:

- Paper 3 established structural separation
- Paper 4 established governance mechanics
- Paper 6 established deterministic enforcement
- Paper 7 established mutation bounding
- Paper 8 established security properties
- Paper 9 (this paper) establishes economic implications — lifecycle, implementation, cognitive, and organizational

Security, determinism, and economics are consequences of the same architectural discipline.

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2. The Complexity Problem in Conventional Systems

2.1 Complexity as the Binding Constraint

Software scaling discussions typically focus on **throughput scaling**: handling more requests, more data, more users. Throughput scaling is largely solved through horizontal scaling, caching, partitioning, and distributed systems.

A second scaling challenge remains unsolved: **complexity scaling**. How do systems accommodate more features, more integrations, more edge cases, more configurations, more organizational stakeholders?

Complexity is the binding constraint because:

- Throughput scaling is solvable with resources
- Complexity scaling is not solvable with resources
- More developers cannot comprehend an incomprehensible system
- They make it more complex

2.2 Characteristics of Conventional Systems

Conventional systems exhibit structural patterns that amplify complexity:

Pattern	Description
Interwoven logic	Business logic and execution code are inseparable
Implicit state mutation	State changes occur without explicit declaration
Informal versioning	Version discipline is procedural, not structural
Non-deterministic drift	Behavior changes through accumulated modifications
Hidden control flow	Execution paths are not fully enumerable

These patterns create **implicit coupling**: components interact through shared state, changes propagate through unexpected pathways, and understanding requires global knowledge.

2.3 The Integration Density Problem

Traditional domain architecture embeds five concerns in imperative code:

- Business rule encoding (what should happen)
- State mutation (where and how data changes)
- Orchestration logic (in what order)
- Cross-module integration (how components interact)
- Error and security semantics (what happens on failure)

These concerns are **syntactically interleaved** — they share the same functions, classes, and modules. No structural boundary separates them.

As capability count n increases, each capability may interact with multiple others. Integration paths grow with the interaction graph — not with capability count alone. The interaction graph density determines integration cost, not the node count.

Claim: In traditional architectures, integration cost is the dominant cost driver at scale — not business logic itself.

2.4 Complexity Growth Patterns

As conventional systems grow, complexity exhibits non-linear growth:

Behavioral coupling growth: If n components can each potentially affect each other, interaction space is $O(n^2)$.

Testing surface explosion: n conditionals produce $O(2^n)$ execution paths.

Debugging entropy increase: Trace ambiguity increases with implementation depth.

Technical debt accumulation: Quick fixes create areas requiring more quick fixes.

Implicit semantic drift: Behavior changes without corresponding specification changes.

2.5 Structural Entropy

We define:

$$\text{Structural Entropy} = \text{Undeclared or implicit behavioral surface}$$

Structural entropy measures the degree to which system behavior is implicit rather than explicit. High entropy systems have large undeclared behavioral surfaces—behavior that occurs but is not specified.

As conventional systems grow, entropy increases non-linearly. Eventually, the system's actual behavior diverges significantly from any specification or understanding.

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3. Defining the Governance Dividend

3.1 Definition

The **Governance Dividend** is the long-term reduction in:

- Behavioral ambiguity
- Mutation surface sprawl
- Change propagation cost
- Testing uncertainty
- Conformance ambiguity

achieved through constitutional constraint.

The governance dividend is not a short-term productivity metric. It is a lifecycle structural property that compounds over time.

3.2 Sources of the Dividend

The governance dividend derives from structural properties established in earlier papers:

Property	Source	Economic Implication
Bounded vocabulary	Paper 3	Finite behavioral surface to maintain
Explicit governance	Paper 4	Change is traceable and auditable
Deterministic execution	Paper 6	Replay and debugging are tractable
Bounded mutation	Paper 7	State change is enumerable
Structural security	Paper 8	Security is architectural, not additive

Each property contributes to reduced lifecycle cost.

3.3 Dividend Accumulation

The governance dividend accumulates because:

1. **Maintenance cost is reduced:** Explicit specifications are easier to maintain than implicit behavior
2. **Evolution cost is reduced:** Controlled change is safer and faster
3. **Operations cost is reduced:** Observable systems are easier to operate
4. **Retirement cost is reduced:** Explicit specifications are easier to migrate

Each phase benefits from prior governance investment. The dividend compounds.

3.4 The Dividend Is Not Productivity Acceleration

The governance dividend is not about writing code faster. Initial development may be slower due to governance overhead.

The dividend is about:

- Sustained velocity over time (vs. degrading velocity)
- Reduced total lifecycle cost (vs. front-loaded savings with back-loaded pain)
- Maintained comprehensibility (vs. growing opacity)
- Controlled evolution (vs. accumulating chaos)

The dividend manifests in the long term, not the short term.

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4. Complexity Scaling Models

4.1 Conventional Complexity Growth

Let N be the number of features or components.

In conventional systems:

$$\text{Interaction Surface} \approx O(N^2)$$

Because: - Components interact through shared state - Each component can potentially affect any other - Changes propagate through implicit pathways

Additional growth factors:

Factor	Growth	Rationale
State space	$O(m^N)$	N components with m states each
Execution paths	$O(2^N)$	N conditionals
Edge cases	$O(k^N)$	N features with k edge cases each interacting

In practice, systems exhibit $O(N^2)$ to $O(N^3)$ complexity growth as size increases. These growth behaviors describe worst-case or integration-dense systems; well-factored conventional systems may approximate sub-quadratic growth but remain vulnerable to emergent coupling over time.

4.2 Protocol-Governed Complexity Growth

In protocol-governed systems:

$$\text{Interaction Surface} \approx O(N \times C)$$

Where C is the bounded concern vocabulary.

Because: - Vocabulary remains bounded (Paper 3) - Mutation surface is finite (Paper 7) - Behavior is version-addressable (Paper 5) - Execution is deterministic (Paper 6)

When C is constant (vocabulary does not expand), growth is:

$$O(N \times C) = O(N)$$

Complexity grows linearly with component count.

4.3 The Scaling Differential

The complexity scaling differential has profound implications:

System Size	Conventional $O(N^2)$	Protocol-Governed $O(N)$	Ratio
10 components	100	10	10×
100 components	10,000	100	100×
1,000 components	1,000,000	1,000	1,000×
10,000 components	100,000,000	10,000	10,000×

The differential increases with scale. Large protocol-governed systems are orders of magnitude less complex than equivalent conventional systems.

4.4 Coupling: Explicit vs. Emergent

The scaling differential arises from how coupling manifests:

Conventional systems: Coupling is emergent. Components interact through implicit pathways that grow combinatorially.

Protocol-governed systems: Coupling is explicit. Components interact only through declared contracts. New components add their declared interactions, not combinatorial possibilities.

Explicit coupling grows additively. Emergent coupling grows multiplicatively.

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5. Technical Debt Inversion

5.1 The Nature of Technical Debt

Technical debt is the implied cost of future rework caused by expedient choices today. Like financial debt, technical debt accrues interest: deferred work becomes more expensive over time.

In conventional systems, technical debt arises from:

Source	Description
Implicit behavior	Undocumented behavior that must be preserved
Mutable semantics	Behavior that changes without explicit versioning
In-place modification	Changes that overwrite rather than version
Lack of coexistence	Inability to run multiple versions simultaneously

Technical debt compounds: quick fixes create areas requiring more quick fixes, creating debt accumulation spirals.

5.2 Debt Accumulation in Conventional Systems

Studies suggest technical debt eventually consumes 40-60% of development capacity in large conventional systems. At this point, most engineering effort goes to debt service rather than new value.

The accumulation pattern:

1. Initial development: Low debt, high velocity
2. Growth phase: Debt accumulates, velocity begins declining
3. Maturity phase: Debt dominates, velocity significantly reduced
4. Legacy phase: Debt service exceeds value creation

5.3 The Inversion Thesis

Protocol governance inverts the debt accumulation curve by enforcing:

Enforcement	Effect
Version immutability	Changes create versions, not overwrites
Explicit amendment	All changes are declared and governed
Referential integrity	References resolve; no dangling dependencies
Trace-based validation	Behavior is verifiable against specification

This shifts cost distribution:

$$\text{Conventional: Low } G_0\text{, High growing } \Delta C$$

$$\text{Protocol-Governed: Higher } G_0\text{, Lower stable } \Delta C$$

Where: - G_0 = Initial governance/design cost - ΔC = Per-change cost

5.4 The Debt Curve Inversion

Over time, the debt curves cross:

Conventional trajectory: - Low initial investment - Debt accumulates - Per-change cost grows - Eventually, change becomes prohibitively expensive

Protocol-governed trajectory: - Higher initial investment - Debt does not accumulate (explicit versioning) - Per-change cost remains stable - Change remains tractable indefinitely

The crossover point depends on system lifespan and change frequency. For non-trivial systems with multi-year lifespans, crossover typically occurs within the first major evolution cycle.

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6. Implementation Cost Topology

6.1 Traditional Domain Cost Decomposition

This section moves from macro-level complexity scaling (Section 4) to micro-level implementation cost analysis. Where Section 4 models *how complexity grows*, this section models *where cost resides* and *how cost structure transforms* under protocol governance.

Define the total implementation cost of a traditional domain with n capabilities:

$$C_{\text{trad}}(n) = C_{\text{logic}}(n) + C_{\text{integration}}(n) + C_{\text{state}}(n) + C_{\text{orchestration}}(n) + C_{\text{security}}(n)$$

Where:

Category	Symbol	Growth Behavior
Business logic	$C_{\text{logic}}(n)$	$O(n)$ — linear with capability count
Integration	$C_{\text{integration}}(n)$	$O(e)$ where e = edges in interaction graph
State management	$C_{\text{state}}(n)$	$O(n \cdot s)$ where s = state surface per capability
Orchestration	$C_{\text{orchestration}}(n)$	$O(n)$ to $O(n \cdot e)$ — ordering + error routing
Security / error	$C_{\text{security}}(n)$	$O(n + e)$ — per capability + per integration path

6.2 The Integration Graph

Model the domain as a directed graph $G = (V, E)$:

- V = capabilities ($|V| = n$)
- E = integration edges (data flow, invocation, error propagation)

In a dense traditional domain:

$$|E| = O(n \cdot k) \text{ where } k = \text{average fan-out per capability}$$

In tightly coupled domains, k grows with n (new capabilities integrate with existing ones):

$$|E| \approx O(n^2) \text{ worst case (fully connected)}$$

$$|E| \approx O(n \log n) \text{ typical well-factored domain}$$

The dominant cost term is integration:

$$C_{\text{trad}}(n) \approx C_{\text{integration}}(n) = O(n \cdot k)$$

This is the structural root of why traditional systems become expensive at scale: **integration cost, not business complexity, drives the budget.**

6.3 Maintenance Amplification

Each business rule change in the traditional model:

- Propagates through integration edges
- Requires regression testing proportional to reachable subgraph
- May trigger cascading state management changes

Maintenance cost per change:

$$C_{\text{change_trad}} \approx O(\text{degree}(v)) \text{ where } v = \text{modified capability}$$

In dense graphs, degree(v) grows with n.

6.4 PGS Cost Decomposition

PGS partitions the same domain into four structurally isolated layers:

$$C_{\text{pgs}}(n) = C_{\text{protocol}} + C_{\text{executor}} + C_{\text{cs}} + C_{\text{ct}}(n)$$

Layer	Symbol	Nature	Growth
Protocol artifacts	C_{protocol}	Declarative YAML — no imperative code	$O(n)$ in artifact count, $O(0)$ in SLOC
Execution engine	C_{executor}	Domain-blind, fixed	$O(1)$ — constant across all domains
Capability side effects	C_{cs}	Backend-aligned adapters	$O(b)$ where b = backend types (finite, small)
Capability transforms	$C_{\text{ct}}(n)$	Domain-function mechanics	See Section 6.5

6.5 The CT Cost Partition

The critical decomposition within the capability transform layer:

$$C_{\text{ct}}(n) = C_{\text{reusable}} + C_{\text{novel}}(n)$$

Where:

- C_{reusable} = cost of context-free atoms available in the shared library (amortized across all domains)
- $C_{\text{novel}}(n)$ = cost of domain-specific atoms not yet in the library

Key property: $C_{\textbf{novel}}(n)$ **is monotonically non-increasing per domain** as the reusable library grows.

For domain d with capability count n_d:

$$C_{\text{novel}}(d) = \sum_{a \in \text{atoms}(d),\, a \notin \text{ReusableLibrary}} \text{atom_cost}(a)$$

6.6 The Amortization Structure

Cost Component	Paid By	Amortized Across
C_{executor}	Platform team (once)	All domains (∞)
C_{cs}	Platform team (once per backend type)	All domains using that backend
C_{reusable}	First domain needing each atom	All subsequent domains
$C_{\text{novel}}(d)$	Domain d team	Domain d only

6.7 Where Integration Went

Critical insight: Integration is not reduced — it is **eliminated as imperative code** and **relocated to declarative protocol.**

In PGS:

- Orchestration order → declared in WF_ workflow DAG
- Data flow between capabilities → declared in CC_ machine block bindings
- Error routing → declared in WF_ outcome edges (SUCCESS, VIOLATION, DENIED)
- Cross-capability dependencies → structural, resolved at build time

The integration graph still exists — but it is a **governance artifact**, not code.

$$C_{\text{integration_pgs}} = 0 \quad \text{(in imperative SLOC)}$$

The integration concern is authored, not coded. It is validated at build time, not tested at runtime.

6.8 Cost Topology Transformation

Traditional scaling:

$$C_{\text{trad}}(n) = \alpha \cdot n + \beta \cdot n \cdot k(n) + \gamma \cdot n \approx O(n \cdot k(n))$$

Where $k(n)$ is the average interaction fan-out, which grows with domain density.

PGS scaling:

Since C_{executor}, C_{cs}, and C_{reusable} are fixed or amortized:

$$C_{\text{pgs}}(n) \approx K + C_{\text{novel}}(n)$$

Where K is the fixed platform cost.

The marginal cost of adding domain d to an existing PGS platform:

$$\Delta C_{\text{pgs}}(d) = C_{\text{protocol}}(d) + C_{\text{novel}}(d)$$

Compare to traditional:

$$\Delta C_{\text{trad}}(d) = C_{\text{logic}}(d) + C_{\text{integration}}(d) + C_{\text{state}}(d) + C_{\text{orchestration}}(d) + C_{\text{security}}(d)$$

6.9 Asymptotic Behavior

As the reusable atom library matures:

$$\lim_{\text{domains}\to\infty} C_{\text{novel}}(d) \to 0$$

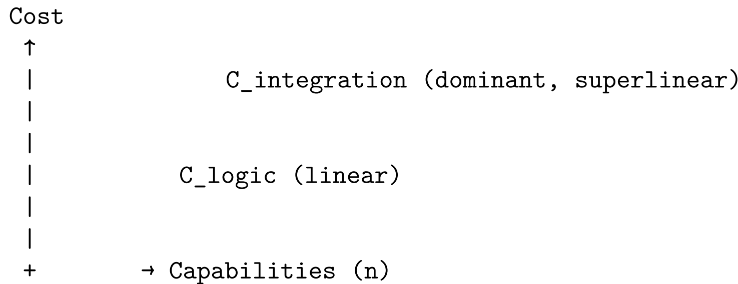
Under the assumption that mechanical transform patterns are finite within a bounded problem class. This holds because:

- Common mechanical patterns (lookup, validate, generate ID, assemble record) are finite
- Each new domain has a higher probability of full reuse
- Novel atoms, once created, join the reusable pool

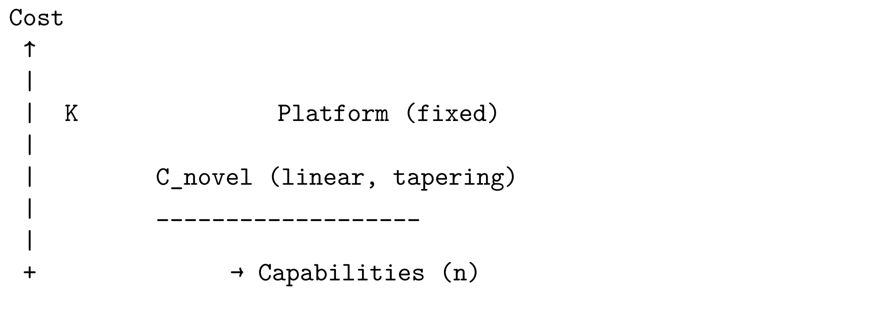
The marginal implementation cost of new domains approaches the cost of authoring governance artifacts alone.

6.10 Topology Contrast

Traditional Domain Cost Topology:



PGS Domain Cost Topology:



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7. The Protocol Dividend

7.1 Definition

The **Protocol Dividend** is the reduction in marginal domain implementation cost achieved by separating governance from execution in a protocol-governed architecture.

$$\text{ProtocolDividend}(d) = \Delta C_{\text{trad}}(d) - \Delta C_{\text{pgs}}(d)$$

The dividend arises not from faster coding, but from the removal of integration as an imperative concern. When orchestration, data flow, and error routing become governance artifacts rather than code, the dominant cost term in traditional implementations vanishes from the imperative surface entirely.

7.2 Decomposition of the Dividend

The Protocol Dividend comprises five structural eliminations:

Eliminated Cost	Mechanism
Integration code	Relocated to declarative protocol artifacts
Orchestration code	Declared in workflow DAG, executed by domain-blind engine
State management boilerplate	Bounded by finite CS adapter set
Regression surface	CTs are context-free; protocol changes don't propagate
Security perimeter code	Vocabulary-bounded; no undeclared behavior possible

7.3 Relationship to Governance Dividend

The Governance Dividend (Section 3) and Protocol Dividend operate at different economic layers:

Concept	Scope	Economic Layer
Governance Dividend	Organizational: reduced coordination, audit, compliance, entropy, and change propagation cost	Lifecycle economics
Protocol Dividend	Implementation: reduced marginal code, integration, and maintenance cost per domain	Implementation economics

Same paradigm. Different economic layers. Complementary.

The Governance Dividend answers: *What does governance save the organization over time?*

The Protocol Dividend answers: *What does governance save per domain added to the platform?*

7.4 The Dividend Growth Property

$$\text{ProtocolDividend}(d) \text{ grows with:}$$

- (a) domain interaction density (more integration eliminated)
- (b) reusable atom library size (less novel code required)
- (c) number of domains on the platform (more amortization)

The Protocol Dividend is not fixed — it **accelerates** as the platform matures.

7.5 The Honest Framing

The Protocol Dividend is largest for organizations maintaining multiple governed domains over time. It is smallest for single-use, exploratory, or research systems. As with the Governance Dividend, the return requires upfront investment in platform and governance discipline.

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8. The Architecture Dividend

8.1 Motivation

The Governance and Protocol Dividends address organizational cost and marginal domain cost respectively. A third dividend addresses a cost category that economic models frequently omit: the human cognitive cost of operating within a software system.

Traditional enterprise systems impose escalating cognitive demands on engineers. As system size grows, each engineer must maintain an expanding mental model of behavioral interactions, implicit coupling, undeclared state mutations, and cross-module side effects. This cognitive load is not a subjective inconvenience — it is an economic cost with measurable proxies in onboarding time, change impact analysis duration, cross-team coordination overhead, and fear-of-change incidents.

8.2 Definition

The **Architecture Dividend** is the structural reduction of human cognitive load achieved by relocating behavioral complexity from application code into governed protocol artifacts.

The dividend is not "developers feel better." It is: **the architecture performs cognitive work that would otherwise reside in human working memory.** Orthogonal authoring, semantic compression, and structural change isolation convert human cognitive scaling into structural scaling. As system size grows, the cognitive load per engineer remains bounded — because the governance surface, not the engineer's mental model, carries the behavioral authority.

8.3 Sources of Cognitive Load in Traditional Systems

In traditional systems, engineers must maintain mental models across multiple dimensions simultaneously:

Cognitive Demand	Traditional System Requirement
Behavioral comprehension	Understand what the system does by reading imperative code distributed across services
Coupling awareness	Track implicit dependencies between components through shared state and indirect invocations
Change simulation	Mentally simulate the propagation effects of a proposed change across the interaction graph
State reasoning	Reason about mutable state across concurrent execution paths
Convention adherence	Remember and apply team conventions that are socially enforced, not structurally enforced

Each dimension scales with system size. In a 200-service traditional system, no individual engineer can hold a complete behavioral model. Knowledge fragments across the team, creating tribal dependencies and coordination bottlenecks.

8.4 Cognitive Load Reduction Under Protocol Governance

Protocol governance reduces cognitive load through three structural mechanisms:

Orthogonal authoring. Each governance artifact is self-contained and independently comprehensible. A capability contract declares its inputs, outputs, transform, and side effect without reference to the broader system context. An engineer modifying a single capability contract need not understand the full workflow topology — the contract's behavioral surface is its declaration.

Semantic compression. Governance artifacts compress behavioral intent into declarative specifications. A workflow DAG that declares seven execution steps with five denial paths communicates in a single readable artifact what would otherwise be distributed across thousands of lines of imperative orchestration code. The engineer reads the specification, not the implementation.

Structural change isolation. Version immutability and artifact-scoped references ensure that changes to one artifact cannot silently affect another. Impact analysis becomes a mechanical operation — trace artifact dependencies — rather than a cognitive simulation of potential propagation paths.

8.5 Quantification Model

Cognitive load is difficult to measure directly, but its economic proxies are observable:

Proxy	Traditional	Protocol-Governed	Reduction Mechanism
Onboarding time	Weeks to months (tribal knowledge transfer)	Days to weeks (artifact reading)	Behavior is declared, not discovered
Change impact analysis	Hours per change (mental simulation)	Minutes per change (artifact dependency trace)	Impact is derivable from references
Cross-team coordination	Meeting-heavy (semantic translation)	Artifact-mediated (shared governance surface)	Protocol replaces oral contracts
Fear-of-change incidents	Growing with system age	Bounded by constitutional admissibility	Change risk is mechanical, not intuitive

Consider a hypothetical 50-person engineering organization maintaining a 200-service traditional system. Conservative estimates suggest:

- **Onboarding:** 3 months per engineer × 15% annual turnover = 7.5 engineer-months per year on knowledge transfer
- **Impact analysis:** 2 hours per change × 500 changes per year = 1,000 hours (125 engineer-days) on mental simulation
- **Coordination meetings:** 5 hours per week × 10 teams = 2,600 hours (325 engineer-days) per year on cross-team synchronization

Under protocol governance, onboarding shifts from oral tradition to artifact reading. Impact analysis shifts from mental simulation to dependency tracing. Cross-team coordination shifts from negotiation to governance artifact review. The Architecture Dividend is the fraction of these costs that the architecture absorbs.

8.6 The Scaling Property

The Architecture Dividend exhibits a critical scaling property: cognitive load per engineer remains bounded as system size grows.

In traditional systems:

$$\text{CognitiveLoad}_{\text{trad}}(N) \propto f(N) \quad \text{where } f \text{ is superlinear}$$

Because each engineer must comprehend an increasing fraction of the interaction graph to perform change impact analysis safely.

In protocol-governed systems:

$$\text{CognitiveLoad}_{\text{pgs}}(N) \approx O(1) \quad \text{per artifact scope}$$

Because governance artifacts are self-contained, artifact dependencies are declared, and the behavioral surface of any component is its governance specification — not the transitive closure of its implicit coupling.

The Architecture Dividend grows with system size: larger systems impose proportionally more cognitive load in traditional architectures while maintaining bounded cognitive load under protocol governance.

8.7 Relationship to Governance and Protocol Dividends

The three dividends operate at distinct economic layers:

Dividend	Scope	Economic Layer	Question Answered
Governance Dividend	Organizational	Lifecycle economics	What does governance save the organization over time?
Protocol Dividend	Implementation	Implementation economics	What does governance save per domain added?
Architecture Dividend	Human / cognitive	Team economics	What does governance save in human comprehension cost?

The dividends are complementary and mutually reinforcing. The Architecture Dividend enables the other two: reduced cognitive load enables faster governance authoring (amplifying the Protocol Dividend) and more reliable change governance (amplifying the Governance Dividend). Conversely, the Protocol Dividend's elimination of integration code directly reduces the cognitive surface engineers must comprehend.

8.8 What the Architecture Dividend Is Not

The Architecture Dividend is not a claim that protocol governance eliminates the need for skilled engineers. Governance artifact authoring requires domain understanding, constitutional reasoning, and design judgment. Novel atom implementation requires engineering competence.

The dividend is the claim that the architecture absorbs cognitive work that would otherwise be performed by human working memory — specifically, the work of comprehending implicit coupling, simulating change propagation, and maintaining cross-component behavioral models. That work does not disappear; it is relocated from human cognition to structural governance.

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9. Change Propagation Discipline

9.1 Change Propagation in Conventional Systems

In conventional systems, behavioral change propagates implicitly:

- A code change may affect behavior in unexpected locations
- Dependencies are not fully enumerable
- Impact analysis requires understanding the entire codebase
- Regression risk grows with system size

Change propagation is **unbounded**: a change in one location may affect any other location through implicit coupling.

9.2 Change Propagation in Protocol-Governed Systems

In protocol-governed systems, behavioral change occurs through:

1. **New artifact version:** Change is expressed as a new versioned artifact
2. **Explicit reference updates:** Consuming artifacts update their references
3. **Governance validation:** Changes pass validation before ratification
4. **Trace verification:** Changes can be verified through replay

Change propagation is **bounded and traceable**: the impact of a change is derivable from artifact references.

9.3 Propagation Cost Reduction

Bounded propagation reduces:

Cost Category	Reduction Mechanism
Analysis cost	Impact is derivable from references
Regression risk	Changes are isolated by versioning
Testing scope	Test the changed artifact and direct dependents
Coordination overhead	Teams can change independently within contract bounds

9.4 The Propagation Multiplier

Change propagation creates a cost multiplier:

$$\text{Change Cost} = \text{Direct Cost} \times \text{Propagation Multiplier}$$

In conventional systems, the propagation multiplier grows with system size and coupling density.

In protocol-governed systems, the propagation multiplier is bounded by declared references.

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10. Testing Surface Analysis

10.1 Testing in Conventional Systems

Testing in conventional systems must account for:

Challenge	Description
Implicit mutation	State changes that are not declared
Dynamic dispatch	Runtime-determined execution paths
Undeclared control paths	Execution flows not visible in specification
Combinatorial explosion	Interaction of features creates exponential test cases

Testing complexity grows combinatorially. Complete testing becomes impossible; testing becomes sampling.

10.2 Testing in Protocol-Governed Systems

Testing in protocol-governed systems benefits from:

Property	Testing Benefit
Explicit DAGs	Workflows enumerate all execution paths
Enumerable mutation	CS_ artifacts enumerate all state changes

Property	Testing Benefit
Declared branch conditions	Control flow is fully specified
Trace equivalence	Behavioral conformance is mechanically verifiable

Testing complexity reduces from behavioral discovery to artifact verification.

10.3 Compositional Testing

Protocol governance enables compositional testing:

Test Level	Scope
Unit tests	Individual transforms with input/output pairs
Contract tests	Implementations satisfy their contracts
Composition tests	Composed artifacts behave as expected
Integration tests	End-to-end behavior through full workflows

Each level builds on lower levels. Comprehensive unit and contract testing reduces integration testing burden.

10.4 Testing Cost Model

Testing cost:

$$\text{Test Cost} = \text{Test Case Count} \times \text{Cost Per Test}$$

In conventional systems, test case count grows combinatorially with features.

In protocol-governed systems, test case count grows linearly (one test suite per artifact, plus composition tests).

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11. Organizational Implications

11.1 Separation of Concerns in Teams

Protocol governance separates organizational concerns:

Function	Responsibility
Domain authoring	Define behavioral specifications in governance artifacts
Governance validation	Validate artifact admissibility
Atom engineering	Implement context-free mechanical transforms
Platform engineering	Maintain executor and CS adapters (amortized)

This separation reduces:

- Role ambiguity
- Cross-team dependency friction
- Informal policy drift

No role requires cross-domain integration knowledge. This is a structural consequence of integration elimination (Section 6.7): when integration is not code, no person needs to understand cross-component wiring.

11.2 Team Autonomy

Protocol governance enables team autonomy:

- Teams own specific protocol artifacts
- Teams can modify their artifacts independently
- Teams must maintain contract compatibility
- Teams do not need to coordinate internal changes

Autonomy enables parallel work without coordination overhead.

11.3 Knowledge Distribution

Protocol artifacts encode knowledge:

Knowledge Type	Artifact Location
Behavioral	Workflows, intents
Interface	Capability contracts
Historical	Version history
Rationale	Governance records

Knowledge distribution reduces bus factor: the organization does not depend on specific individuals knowing specific things.

11.4 Onboarding Efficiency

New team members onboard more efficiently:

- Read artifacts to understand behavior
- Read contracts to understand interfaces
- Read governance records to understand history
- Work locally without global understanding

Onboarding is proportional to component scope, not system scope.

New domains require:

1. Governance artifact authoring (protocol skill, not coding skill)
2. Novel atom implementation (only if reusable library lacks needed mechanics)
3. Test payload creation (one per execution path)

No framework learning. No integration architecture. No orchestration coding.

11.5 Governance as Institutional Memory

Governance becomes institutional rather than tribal:

- Policy is encoded in governance rules, not individual heads
- Decisions are recorded in governance records, not lost to turnover
- Standards are enforced by validation, not social pressure

Institutional governance survives personnel changes.

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12. Entropy Containment

12.1 Behavioral Entropy Defined

$$\text{Behavioral Entropy} = \text{Degree of undeclared behavioral freedom}$$

High entropy systems have large undeclared behavioral surfaces—many behaviors are possible but not specified. Low entropy systems have small undeclared surfaces—behaviors are either specified or impossible.

12.2 Entropy Growth in Conventional Systems

In conventional systems, entropy grows through:

- Implicit behavior additions (features with undeclared edge cases)
- Mutation surface expansion (new state access patterns)
- Control flow complexity (new execution paths)
- Configuration proliferation (new behavioral variants)

Entropy grows with every change because changes add implicit behavioral freedom.

12.3 Entropy Containment in Protocol Governance

Protocol governance contains entropy by:

Mechanism	Entropy Effect
Bounded vocabulary	New concerns require constitutional amendment
Prohibited implicit mutation	All mutation is declared
Version immutability	Past behavior is preserved exactly
Eliminated ambient authority	No implicit permission accumulation

Entropy grows only through constitutional amendment, not through incidental change.

12.4 The Entropy Containment Property

$$\frac{d(\text{Entropy})}{d(\text{Change})} \approx 0 \quad \text{(protocol-governed)}$$

$$\frac{d(\text{Entropy})}{d(\text{Change})} > 0 \quad \text{(conventional)}$$

In protocol-governed systems, changes do not inherently add entropy because changes are explicit and bounded. In conventional systems, changes inherently add entropy through implicit behavioral expansion.

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13. Security and Audit Surface Reduction

13.1 Common Foundation

Security (Paper 8), determinism (Paper 6), and economics (this paper) share a common foundation:

- **Bounded vocabulary** (Paper 3) enables security analysis, deterministic routing, and complexity bounding
- **Mutation bounding** (Paper 7) enables attack surface reduction, replay safety, and maintenance tractability
- **Governance enforcement** (Paper 4) enables trust rooting, constitutional discipline, and change control

The same architectural properties yield different benefits in different dimensions.

13.2 Attack Surface as a Function of Code Surface

Attack surface is proportional to mutable imperative code surface:

$$\text{AttackSurface}_{\text{trad}} \propto C_{\text{trad}}(n) \quad \text{(grows with integration density)}$$

$$\text{AttackSurface}_{\text{pgs}} \propto C_{\text{ct}}(n) \quad \text{(grows only with novel atoms)}$$

Since $C_{\text{ct}}(n) \ll C_{\text{trad}}(n)$, the attack surface is structurally compressed.

Property	Traditional	PGS
Code paths containing business logic	Distributed across codebase	Zero — logic is in protocol
Undeclared behavior possible	Yes (any code can execute)	No (vocabulary-bounded)
State mutation surface	Unbounded (any function can write)	Bounded by CS adapter set
Audit requires	Log forensics across services	Deterministic trace inspection

13.3 Complementary Analysis

The papers provide complementary analyses:

Paper	Question	Answer
Paper 6	How is behavior enforced?	Deterministic DAG execution
Paper 7	What constitutes mutation?	CT_/CS_ separation
Paper 8	What are security implications?	Vocabulary-bounded security
Paper 9	What are economic implications?	Governance + protocol + architecture dividends

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14. Empirical Validation — Agent Governance Domain

14.1 Validation Approach

Rather than fabricate traditional system comparisons, we validate the cost model through structural measurement of a greenfield domain implementation. We measure what the model predicts: fixed platform cost, amortized substrate cost, and marginal domain cost. We then enumerate the structural concerns that a traditional implementation would require that PGS eliminates — without inventing SLOC estimates.

14.2 Domain Characteristics

The AI Agent Governance domain governs agent-proposed actions through a constitutional pipeline: normalize request, verify tool declaration, resolve license tier, bind license to tool surface, validate parameters, then record authorized action or denied action.

Dimension	Measure
Business complexity	7 capability contracts, 5 denial paths, 2 authorization paths

Dimension	Measure
Governance artifacts	15 total (7 CC, 1 WF, 1 IN, 2 EV, 3 AC, 1 RB)
Cross-domain data	Reads license facts from ai_licensing domain
Test scenarios	7 payloads covering all execution paths

This is a non-trivial enterprise domain: it enforces multi-step authorization with cross-domain data consumption, multiple denial classifications, and audit recording.

14.3 Implementation Cost Measurement

Cost Component	Measure	Notes
$C_{\text{protocol}}(d)$	15 YAML/MD artifacts	Declarative authoring only
$C_{\text{novel}}(d)$	**0 atoms**	All 4 CT atoms reused from library
C_{cs} additions	**0 adapters**	All 3 CS types reused from substrate
C_{executor} changes	**0 SLOC**	Zero engine modifications
Custom Python	**0 SLOC**	Entire domain is pure protocol

14.4 Platform Context

Platform Asset	Size	Shared By
Execution engine	3,402 SLOC	3 domains (blockchain, ai_licensing, agent_governance)
Reusable substrate	2,877 SLOC	3 domains
Reusable CT atoms	19 atom types	Available to all domains
CS runtime types	4 adapter types	Available to all domains

14.5 Observed Protocol Dividend

For the agent_governance domain:

$$\Delta C_{\text{pgs}}(\text{agent_governance}) = C_{\text{protocol}} + C_{\text{novel}} = 15 \text{ artifacts} + 0 \text{ SLOC}$$

The incremental implementation cost of a non-trivial enterprise domain was **zero imperative code.**

The model predicts (Section 6.9) that as the reusable library matures, $C_{\text{novel}}(d) \to 0$. The agent_governance domain — the third domain on the platform — empirically confirms this prediction. The marginal cost was governance authoring effort alone.

14.6 Observed Architecture Dividend

The agent_governance domain further validates the Architecture Dividend:

Cognitive Proxy	Observation
Domain comprehension	15 governance artifacts fully specify behavior; no imperative code to trace
Change impact analysis	Artifact dependency graph is self-contained; modification to any CC_ affects only that contract
Onboarding surface	New engineer reads 15 artifacts, not a distributed codebase
Cross-domain reasoning	License data consumption is a declared CS binding, not an API integration requiring coupling knowledge

The cognitive surface of the domain is its governance artifact set — finite, enumerable, and self-documenting. A traditional implementation of equivalent functionality would distribute the same behavioral complexity across services, handlers, middleware, database schemas, and orchestration configuration, requiring engineers to maintain a mental model of the full interaction graph.

14.7 Structural Comparison

We do not fabricate SLOC comparisons. Instead, we enumerate the structural concerns a traditional implementation must address that PGS structurally eliminates:

Concern	Traditional Requirement	PGS Requirement
Request normalization	Custom middleware/service	Reusable CT atom
Tool registry lookup	Service + database integration	Reusable CT atom + CS read
License resolution	Service + cross-domain API	Reusable CT atom + CS read
Parameter validation	Custom validation framework	Reusable CT atom
Action recording	Audit service + DB integration	Reusable CS adapter
Denial recording	Separate audit path + DB	Same CS adapter, different binding
Orchestration	Service mesh / workflow engine	Declared in WF_ artifact
Error routing	Custom error handling per path	Declared in WF_ outcome edges
Integration testing	Combinatorial path coverage	Structural: 7 payloads cover 7 paths
Cross-domain coupling	API contracts, versioning	Read-only data via CS binding

Each row represents integration cost that exists in traditional implementations and is **structurally absent** in PGS.

14.8 Validation of Model Predictions

Model Prediction	Empirical Result
C_{executor} is fixed across domains	Confirmed: 0 engine changes for 3rd domain
C_{cs} is bounded and reusable	Confirmed: 0 new CS adapters; 3 types shared
$C_{\text{novel}}(d) \to 0$ as library matures	Confirmed: 0 novel atoms for agent_governance
Integration cost = 0 in imperative SLOC	Confirmed: all orchestration in WF_ artifact

Model Prediction	Empirical Result
Marginal cost C_{protocol}	Confirmed: 15 artifacts, 0 code
Cognitive surface = artifact set	Confirmed: 15 artifacts fully specify domain behavior

14.9 Further Validation Opportunities

Future research may extend validation through:

Metric	Measurement Approach
Change propagation	Measure artifacts affected per change
Defect density	Compare defects per artifact over time
Regression incidence	Measure regressions per change
Trace replay reliability	Measure replay success rates
Maintenance velocity	Measure time to implement changes over system age
Onboarding duration	Measure time-to-productivity for new engineers under governance vs. traditional
Coordination overhead	Measure cross-team meeting hours per change under governance vs. traditional

Comparative studies between conventional and protocol-governed implementations of equivalent functionality would provide additional empirical evidence.

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15. Limits of the Three Dividends

15.1 What This Paper Does Not Claim

This paper does not claim:

- **Zero complexity:** Protocol-governed systems have complexity; it grows linearly rather than polynomially.
- **Zero bugs:** Implementation bugs remain possible in CT_ and CS_ implementations.
- **Infinite scalability:** Physical and organizational limits still apply.
- **Elimination of poor governance:** Bad governance decisions create bad systems.
- **Universal optimality:** The model is not suited to all system types (see Section 15.3).
- **Zero cognitive load:** Engineers must still comprehend governance artifacts, author specifications, and reason about domain semantics. The claim is bounded load, not absent load.

15.2 Where Complexity Resides

Governance shifts where complexity resides:

From: Runtime unpredictability

To: Constitutional discipline

Complexity does not disappear. It is relocated from implicit runtime emergence to explicit constitutional specification.

15.3 Where the Model Weakens

Tradeoff	Description
Authoring overhead	Governance-first requires upfront specification before any execution
Architectural investment	Platform (executor + substrate) must exist before first domain
Toolchain dependence	Builder, validator, and trace infrastructure are prerequisites
Exploratory prototyping	PGS adds friction where rapid informal experimentation is needed
Performance overhead	Protocol indirection may add latency in ultra-low-latency hot paths
Dynamic schemas	Domains with highly dynamic schemas resist vocabulary boundedness
Early-platform cost	When the reusable atom library is immature, C_{novel} is high

PGS optimizes for systems that must remain correct under change. The dividends are largest for organizations maintaining multiple governed domains over time. They are smallest for single-use, exploratory, or research systems.

15.4 The Governance Quality Dependency

All three dividends depend on governance quality:

- If governance is weak, artifacts may be poorly specified
- If validation is incomplete, invalid artifacts may be ratified
- If vocabulary expands undisciplined, complexity bounds weaken
- If change governance is bypassed, implicit changes occur

If governance is weak, all three dividends collapse.

15.5 Investment Requirements

Realizing the dividends requires investment:

Investment	Purpose
Tooling	Authoring, validation, and runtime infrastructure
Training	Developers must learn protocol-governed design
Process	Governance processes must be established
Culture	Organizational commitment to constitutional discipline

These investments have upfront cost. The dividends accrue over time.

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16. Structural Consequences

Protocol governance yields structural consequences for lifecycle, implementation, and cognitive economics:

Property	Structural Cause	Economic Effect
Bounded interaction growth — $O(N)$	Vocabulary-bounded concern surface	Systems scale without combinatorial complexity explosion
Stable mutation surface — $\lvert \text{CS_} \rvert < \infty$	Declared side-effect adapters only	Maintenance teams enumerate all state-changing operations
Deterministic change discipline	Version → Governance → Ratification	Organizations maintain change control at scale
Reduced regression ambiguity	Regression → Trace → Artifact Version	Debugging time reduced; targeted rollback enabled
Stable maintenance cost — $\frac{d(\text{Cost})}{d(t)} \approx 0$	No implicit behavioral expansion	Sustainable long-term system operation
Bounded cognitive load — $O(1)$ per artifact scope	Self-contained governance artifacts	Engineering teams scale without proportional comprehension cost

16.1 Asymptotic Domain Cost Compression

Marginal domain implementation cost decreases as the platform matures:

$$\frac{d(C_{\text{novel}})}{d(\text{domains})} \leq 0$$

Each domain added to the platform enriches the reusable atom library, reducing the novel implementation cost for subsequent domains.

16.2 Cumulative Dividend

The combined governance, protocol, and architecture dividends are cumulative:

$$\text{Dividend}(t) = \int_0^t (\text{Cost}_{\text{conventional}}(\tau) - \text{Cost}_{\text{governed}}(\tau))\, d\tau$$

The dividend grows over time as conventional systems accumulate debt and cognitive burden while protocol-governed systems maintain stability, compress marginal domain cost, and bound per-engineer cognitive load.

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17. Conclusion

Protocol-governed systems redistribute cost from implicit runtime complexity to explicit constitutional design, restructure domain implementation from integration-coupled monoliths to compositionally isolated layers, and relocate behavioral comprehension from human working memory to self-documenting governance artifacts.

This redistribution produces:

Outcome	Mechanism
Lower long-term behavioral entropy	Bounded vocabulary, explicit mutation
Controlled evolution	Versioned change, governance validation
Stable mutation boundaries	Finite CS_ surface, scope enforcement
Deterministic enforcement	DAG execution, trace emission
Eliminated integration code	Orchestration relocated to declarative protocol

Outcome	Mechanism
Asymptotic cost compression	Reusable atoms + amortized platform
Bounded cognitive load	Self-contained artifacts, declared dependencies, structural change isolation

This paper defines three complementary economic properties:

The **Governance Dividend** is structural entropy containment over the system lifecycle — reducing coordination, audit, and change propagation cost at the organizational level.

The **Protocol Dividend** is marginal domain cost compression — reducing implementation, integration, and maintenance cost for each domain added to the platform.

The **Architecture Dividend** is cognitive load absorption — reducing onboarding, change analysis, and cross-team coordination cost by relocating behavioral authority from human comprehension to structural governance.

The three dividends operate at distinct economic layers:

Dividend	Economic Layer	Question Answered
Governance	Lifecycle economics	What does governance save the organization over time?
Protocol	Implementation economics	What does governance save per domain added to the platform?
Architecture	Team economics	What does governance save in human comprehension cost?

The economic model:

$$\text{Total Cost} = \text{Initial Investment} + \sum \text{Change Costs} + \sum \text{Cognitive Costs}$$

For conventional systems, change costs grow over time and cognitive costs scale with system size. For protocol-governed systems, change costs remain stable and cognitive costs remain bounded per artifact scope. The crossover point determines when governance investment becomes favorable; for non-trivial systems with multi-year lifespans, this crossover typically occurs early in the lifecycle.

The implementation cost model:

$$\Delta C_{\text{pgs}}(d) = C_{\text{protocol}}(d) + C_{\text{novel}}(d)$$

As the reusable library matures, $C_{\text{novel}}(d) \to 0$. Marginal domain cost approaches governance authoring alone. Empirical validation confirms this: the AI Agent Governance domain — a non-trivial enterprise domain with 7 capability contracts, 5 denial paths, and cross-domain data consumption — required zero imperative code, zero engine modifications, and zero novel capability transforms.

The scaling model:

$$\text{Complexity}_{\text{conventional}} \approx O(N^2) \text{ (integration-dense systems)}$$

$$\text{Complexity}_{\text{governed}} = O(N) \text{ (vocabulary-bounded composition)}$$

The differential increases with scale and integration density.

The cognitive scaling model:

$$\text{CognitiveLoad}_{\text{conventional}} \propto f(N) \quad \text{(superlinear with system size)}$$

$$\text{CognitiveLoad}_{\text{governed}} \approx O(1) \quad \text{(per artifact scope)}$$

The relationship between papers establishes the complete value model:

> **Governance (Paper 4) makes behavior admissible. Execution (Paper 6) enforces behavior deterministically. Mutation Boundary (Paper 7) separates computation from state change. Security (Paper 8) emerges from structural constraints. Economics (this paper) demonstrates lifecycle returns, implementation cost compression, and cognitive load absorption.**

The three dividends are real and substantial. Organizations that invest in protocol governance will realize compounding returns through reduced maintenance cost, sustained change velocity, compressed marginal domain cost, bounded cognitive load, and manageable complexity at scale.

The central insight is that integration — historically the dominant cost driver in software — is no longer a coding problem. When orchestration, error routing, and cross-capability binding become governance artifacts, the domain ceases to exist as a tightly coupled executable graph and becomes a composition of context-free mechanics under constitutional law. Simultaneously, behavioral comprehension ceases to be a human memory problem — the governance surface carries the behavioral authority that would otherwise reside in engineers' mental models.

Constitutional discipline sustains what determinism and security make possible.

Appendix A — Notation Summary

Symbol	Definition
N or n	Component or capability count
$k(n)$	Average interaction fan-out per capability
$C_{\text{trad}}(n)$	Total traditional implementation cost
$C_{\text{pgs}}(n)$	Total PGS implementation cost
C_{protocol}	Cost of declarative governance artifacts (no SLOC)
C_{executor}	Fixed execution engine cost (domain-blind)
C_{cs}	Bounded capability side-effect adapter cost
$C_{\text{ct}}(n)$	Capability transform cost
C_{reusable}	Amortized reusable atom library cost
$C_{\text{novel}}(d)$	Domain-specific novel atom cost
K	Fixed platform cost ($C_{\text{executor}} + C_{\text{cs}} + C_{\text{reusable}}$)
$\Delta C(d)$	Marginal cost of adding domain d
$\text{ProtocolDividend}(d)$	$\Delta C_{\text{trad}}(d) - \Delta C_{\text{pgs}}(d)$
G_0	Initial governance/design cost
ΔC	Per-change cost
b	Backend type count (finite)
$\text{CognitiveLoad}(N)$	Human comprehension cost as function of system size

Appendix B — Empirical Reference Data

Measurements from the OmniBachi reference implementation:

Measurement	Value	Source
Execution engine SLOC	3,402	execution/ directory
Reusable substrate SLOC	2,877	reusable/ directory
Reusable CT atom types	19	reusable/capability_transforms/atoms/
CS runtime adapter types	4	reusable/capability_side_effects/
Domains sharing platform	3	blockchain, ai_licensing, agent_governance
Agent governance artifacts	15	7 CC, 1 WF, 1 IN, 2 EV, 3 AC, 1 RB
Agent governance CTs used	4 (100% reusable)	CT_PURE_GENERATE_ID, LOOKUP, VALIDATE_SET_MEMBERSHIP, VALIDATE_PARAMETER_RULES
Agent governance CSs used	3 (100% reusable)	MutableJson, Registry, AppendOnlyJsonl
Agent governance novel atoms	0	Zero domain-specific CT implementations
Agent governance custom Python	0 SLOC	Entire domain is declarative protocol
Agent governance engine changes	0 SLOC	Zero modifications to execution/
Agent governance test scenarios	7	2 happy paths, 5 denial paths

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