SPAK: A Spec-Driven Kernel for Systematic Intelligence Engineering

Abstract

We introduce **Systematic Intelligence Engineering (SIE)**, a principled engineering framework for constructing reliable, verifiable, and evolvable autonomous systems. SIE is founded on the premise that robustness in intelligent systems emerges not from increasingly capable foundation models alone, but from architectural separation between heuristic reasoning and mechanized execution.

To operationalize SIE, we present the **Spec-driven Programmatic Agent Kernel (SPAK)**, a minimal runtime kernel that enforces correctness through executable specifications, invariant checking, and effect isolation. SPAK treats agent behavior as a compilable artifact rather than an unstructured prompt, enabling formal validation, auditability, and reproducibility.

As empirical validation, we implement a **six-level agent curriculum** that progressively increases agent autonomy and architectural complexity—from static responders to recursive self-solvers—while running entirely on the same kernel. This demonstrates that SPAK provides a stable abstraction layer for a broad class of agent systems.

We further position SPAK as the foundational kernel for **Autonomous Engineering Systems (AES)** and outline a meta-level supervision loop that enables systematic self-improvement through specification evolution. This work establishes a concrete path from ad-hoc agent scripting to a disciplined engineering practice for intelligent systems.

Contributions: 1. Formalization of **Systematic Intelligence Engineering (SIE)** as an engineering discipline. 2. Design and implementation of **SPAK**, a spec-driven kernel for agents. 3. A formally defined **Dual Validation** mechanism separating reasoning alignment and domain correctness. 4. A graded **agent curriculum** demonstrating architectural scalability. 5. An extensible architectural blueprint for future self-improving **Autonomous Engineering Systems**.

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1. Introduction

Recent advances in large language models (LLMs) have enabled agents capable of reasoning, tool use, and planning. However, most contemporary agent systems remain fragile, difficult to verify, and resistant to systematic improvement. These systems rely heavily on prompt engineering, entangling probabilistic reasoning with execution logic in ways that are neither inspectable nor enforceable.

This paper argues that intelligent systems must be engineered, not merely prompted. We propose **Systematic Intelligence Engineering (SIE)**, an engineering paradigm that treats intelligent behavior as a composition of formally specified components executed under strict runtime supervision.

Core Thesis. Reliability in autonomous systems is primarily an architectural problem. Robust intelligence emerges when heuristic reasoning is isolated from deterministic execution, and when all behavior is mediated by explicit specifications and invariant enforcement.

To support this thesis, we introduce **SPAK**, a kernel-level runtime for agents that enforces this separation and provides the minimal primitives required for building reliable autonomous systems.

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2. Systematic Intelligence Engineering (SIE)

2.1 Definition

Systematic Intelligence Engineering (SIE) is defined as:

> A discipline for designing, implementing, and evolving intelligent systems through explicit specifications, invariant-preserving execution, and hierarchical supervision.

SIE draws inspiration from systems engineering, programming language theory, and safety-critical software design. It rejects end-to-end opaque intelligence in favor of composable, verifiable, and evolvable intelligence.

2.2 Design Principles

SIE is governed by the following principles:

1. **Specification Primacy**: All agent behavior must be derived from explicit, machine-readable specifications.
2. **Heuristic–Mechanism Separation**: Probabilistic reasoning proposes actions; deterministic systems validate and execute them.
3. **Invariant Preservation**: Domain laws must be enforced at runtime, not assumed.
4. **Traceability**: All decisions and state transitions must be auditable.
5. **Hierarchical Supervision**: Learning and self-improvement occur at a level above execution.

2.3 SIE Architectural Layers

SIE structures intelligent systems into four conceptual layers:

1. **Kernel Layer (SPAK)**: Enforces execution semantics, validation, and effect handling.
2. **System Layer (AES)**: Composes multiple agents and workflows to solve real-world engineering tasks.
3. **Methodological Layer (SIE)**: Defines design rules and correctness criteria.
4. **Meta-Level Supervision**: Analyzes system behavior to guide improvement and evolution.

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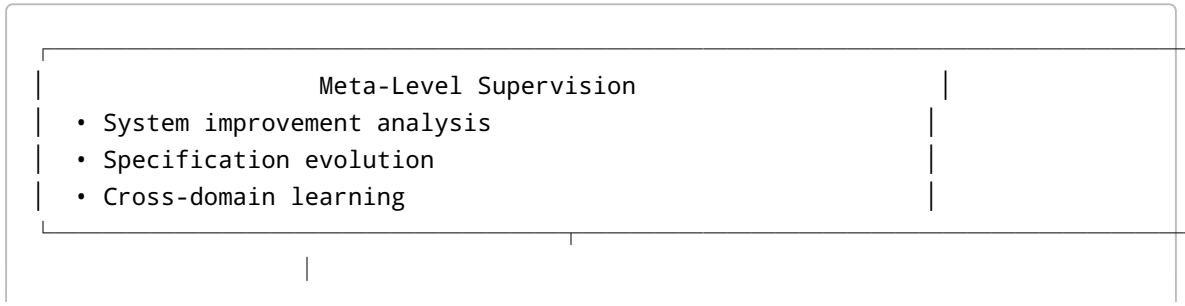
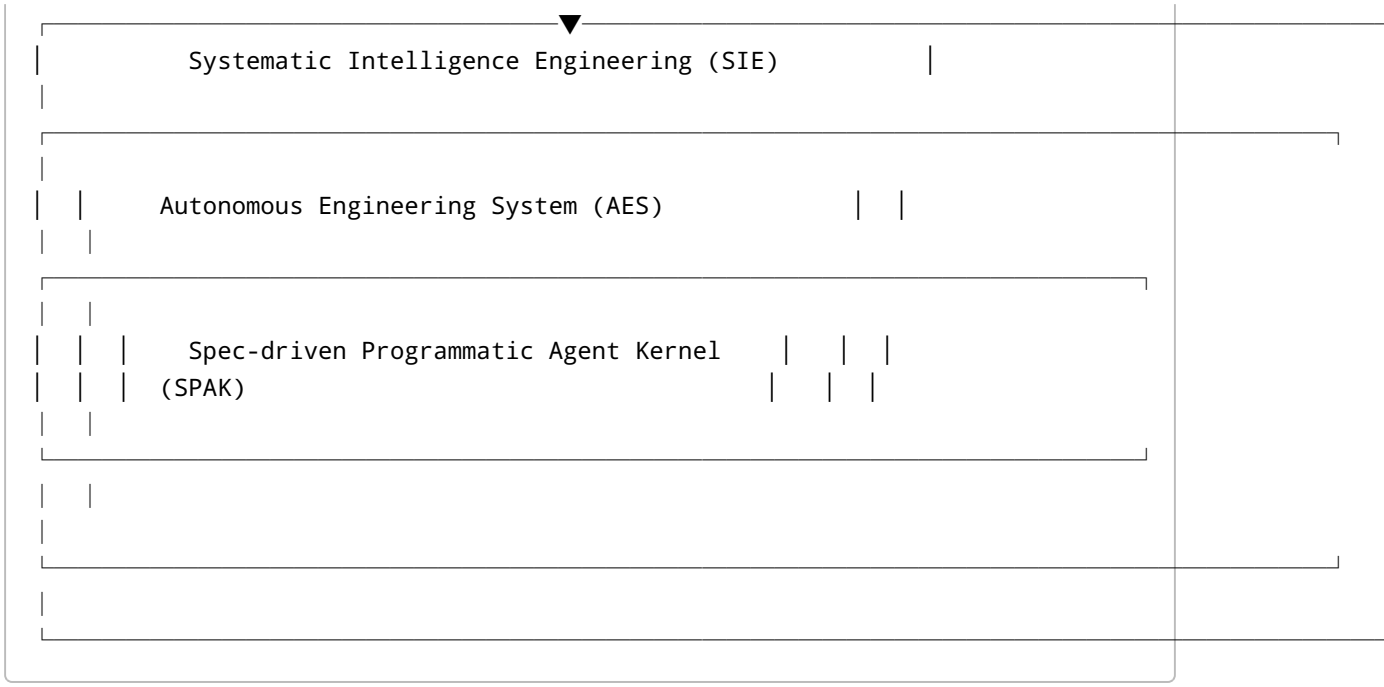
3. Architectural Overview





This layered decomposition ensures that learning, execution, and evolution remain decoupled, preventing uncontrolled behavioral drift.

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4. The SPAK Kernel

4.1 Executable Specifications (AgentSpec)

Agents in SPAK are defined by **AgentSpec**, a domain-specific language capturing: - **Domain Model**: Typed state schemas and legal transitions. - **Invariants**: Constraints that must hold across all executions. - **Workflow**: Structured control flow and agent lifecycle.

AgentSpec compiles into both prompt context for LLM reasoning and runtime validators for execution, ensuring semantic alignment.

4.2 Dual Validation Framework

SPAK enforces correctness through **Dual Validation**, defined as follows.

Definition 1 (Operational Consistency Validation). Given a reasoning trace R and a symbolic action plan P, operational consistency holds if:

$$\mathcal{V}_{\text{op}}(R, P) = \text{true}$$

where R semantically entails P. This validation ensures that the agent's reasoning aligns with its declared intentions.

Definition 2 (Domain Invariant Validation). Given a plan execution result E and a set of invariants I, domain validity holds if:

$$\forall i \in I,\ i(E) = \text{true}$$

Execution is permitted if and only if both validations succeed:

$$\mathcal{V}_{\text{dual}} = \mathcal{V}_{\text{op}} \wedge \mathcal{V}_{\text{dom}}$$

TODO: Formalize semantic entailment metrics for $\mathcal{V}_{\text{op}}$.

4.3 Effect Isolation

All external interactions are modeled as algebraic effects. Agents may request effects, but the kernel decides whether and how they are executed.

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5. Experimental Validation: Agent Curriculum

We validate SPAK via a six-level agent curriculum demonstrating architectural scalability.

Level	Agent Type	Demonstrated Concept
0	Static Responder	Pure morphism
1	Context-Aware Agent	Immutable state
2	Tool-Use Agent	Effect handling
3	Planning Agent	Traceability
4	Multi-Agent System	Composition
5	Recursive Solver	Fractal kernel reuse

All agents share the same kernel, demonstrating abstraction stability.

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6. Related Work

6.1 Agent Frameworks

Existing agent frameworks such as **AutoGPT**, **BabyAGI**, **LangChain**, **LlamaIndex**, and **Semantic Kernel** emphasize orchestration and prompt composition. While effective for rapid prototyping, these systems lack formal execution semantics, invariant enforcement, and kernel-level isolation.

6.2 Programming Language and Systems Foundations

SPAK draws from algebraic effects, functional programming, and operating system kernels. Prior work in effect systems and capability-based security informs SPAK's design but has not been applied systematically to LLM-driven agents.

6.3 Verification and Safe AI

Formal verification efforts in AI largely focus on model behavior. SIE instead verifies system behavior, positioning correctness as a runtime property.

TODO: Expand comparison with agent verification and program synthesis literature.

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7. Autonomous Engineering Systems (AES)

An **Autonomous Engineering System (AES)** is defined as:

> A system composed of multiple SPAK-governed agents capable of executing complex engineering workflows under invariant enforcement.

AES instances operate entirely in user space atop SPAK, inheriting its guarantees while enabling domain-specific intelligence.

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8. Meta-Level Supervision and Future Work

The final layer of SIE is **meta-level supervision**, responsible for analyzing traces, failures, and performance regressions.

Future research directions include: - Automated invariant discovery (TODO) - Spec evolution via meta-learning (TODO) - Cross-domain transfer of specifications (TODO)

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9. Conclusion

This paper formalizes Systematic Intelligence Engineering and introduces SPAK as its foundational kernel. By separating reasoning from execution and enforcing correctness through dual validation, SPAK enables a transition from ad-hoc agent scripts to disciplined autonomous engineering systems.

We argue that future advances in AI reliability will be driven less by larger models and more by stronger architectural foundations.