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# Behavioral Verification via PRD-Derived Property-Based Testing: Eliminating Semantic Drift in Autonomous Agents

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## Abstract

Autonomous software development agents often suffer from semantic drift, where generated code passes superficial validation but fails to satisfy the underlying functional requirements due to reliance on loose lexical similarity checks. To address this, we propose a formal behavioral verification layer that integrates Property-Based Testing (PBT) directly into the agent lifecycle. Our system automatically synthesizes strict logical invariants from product requirement documents and enforces a mandatory verification gate that prevents the agent from proceeding until all functional properties hold. We implemented this pipeline within the Wreckit autonomous framework, introducing a self-correction mechanism where invariant failures trigger counterexample-driven regression loops. We evaluated the method using a dataset of twenty complex feature requests, comparing the enhanced system against a baseline implementation to measure semantic drift reduction and operational efficiency. The experimental results demonstrate that the proposed approach effectively eliminates intent drift while maintaining system performance, achieving a 100% success rate in autonomous refactoring and 95% adherence to roadmap execution goals. Furthermore, the verification layer imposes negligible computational overhead, supporting high concurrency scaling with zero file system corruption.

## 1 Introduction

The rapid evolution of autonomous software development agents has enabled the automated generation of complex codebases, yet ensuring the functional correctness of this code remains a significant bottleneck. While current frameworks demonstrate proficiency in syntactic generation, they frequently suffer from a phenomenon known as semantic drift, where the generated code passes superficial validation checks but fails to satisfy the underlying business logic. This limitation stems from a reliance on loose lexical similarity metrics and example-based unit testing, which are insufficient for verifying the rigorous invariants required in production software. Because large language models are inherently probabilistic and optimized for pattern matching, they can produce implementations that are syntactically correct and pass narrow unit tests while violating the fundamental intent of the product requirements. Distinguishing between code that merely compiles and code that faithfully implements complex logic is a difficult challenge that existing autonomous agents struggle to overcome without human intervention.

To address this fragility, we propose a formal behavioral verification layer that integrates Property-Based Testing (PBT) directly into the agent development lifecycle. Unlike traditional testing that checks specific input-output pairs, PBT allows for the specification of universal invariants, such that for all inputs  $x$ , the property  $P(x)$  must hold. Our system

automatically synthesizes these strict logical constraints from Product Requirement Documents (PRDs), transforming user stories and acceptance criteria into executable verification code. By enforcing a mandatory verification gate, the agent is prohibited from proceeding until all generated invariants are satisfied, thereby anchoring execution to functional behavior rather than text similarity. This approach replaces the validation of surface-level features with a rigorous mathematical check of the system’s operational characteristics.

We operationalize this approach within the Wreckit autonomous framework by extending its state machine to include specific phases for property generation and verification. The pipeline intercepts the `prd.json` artifact to generate TypeScript invariants using a testing framework like `fast-check`. Crucially, the system introduces a self-correction mechanism: if the behavioral gate detects a violation, the resulting counterexample is logged and triggers a regression loop, forcing the agent back to a planning state to address the specific logical error. This feedback loop ensures that the agent iterates not just on code syntax, but on the logical correctness of the implementation relative to the requirements, utilizing the logged counterexamples to guide the repair process.

To validate the efficacy of this method, we conducted a comparative experiment using a dataset of twenty complex feature requests against a standard baseline implementation. We evaluated the system based on the reduction of semantic drift, the efficiency of the regression loops in converging on a correct solution, and the computational overhead imposed by the verification layer. The experimental results demonstrate that our approach effectively eliminates intent drift, achieving a 100% success rate in autonomous refactoring while maintaining high concurrency and imposing negligible overhead. By shifting the validation paradigm from lexical similarity to formal invariant checking, this work establishes a robust foundation for reliable autonomous software engineering.

## 2 Methods

### 2.1 System Architecture and State Machine Extension

To operationalize the proposed behavioral verification layer, we modified the existing Wreckit autonomous development framework. The core architectural change involves extending the Wreckit state machine to support formal verification logic. We introduced two transient states, `generating_properties` and `verifying`, into the agent lifecycle. The modified transition logic enforces the following flow: `planned`  $\rightarrow$  `generating_properties`  $\rightarrow$  `implementing`  $\rightarrow$  `verifying`  $\rightarrow$  `in_pr`. In cases where verification fails, the system regresses from `verifying` back to `planned`, initiating a self-correction loop.

We extended the artifact management system by updating the Zod schema validation to accommodate new verification artifacts. Specifically, the system now manages `.wreckit/properties/invariants.ts`, which houses the generated TypeScript test code, and `.wreckit/counterexamples.json`, a structured log for recording specific input failures that trigger regression. Furthermore, we defined a new prompt template, `pbt_generator.md`, designed to ingest the Product Requirement Document (PRD) and a unique identifier. This template instructs the Large Language Model (LLM) to translate acceptance criteria into universally quantified properties, explicitly forbidding the generation of example-based unit tests in favor of invariants.

### 2.2 Property-Based Testing Pipeline Implementation

The implementation of the verification pipeline was executed using the Claude Agent SDK and is divided into three distinct phases: Property Synthesis, Behavioral Gatekeeping, and Self-Correction.

#### 2.2.1 Phase A: Property Synthesis

Immediately following the successful generation of the `prd.json` artifact, the system triggers the `generating_properties` state. We utilize the Claude Agent SDK to process the `pbt_generator.md` template. The output is validated using Zod to ensure

it constitutes a parsable TypeScript file containing at least one `fc.property` call (utilizing the `fast-check` framework). Once validated, the invariant code is written to `.wreckit/properties/invariants.ts`. This step automates the transformation of natural language requirements into executable logical constraints.

### 2.2.2 Phase B: Behavioral Gatekeeping

After the agent completes the `implementing` phase and generates code modifications, the Watchdog Watcher triggers the `verifying` state rather than proceeding directly to the pull request phase. The system executes the test suite defined in `invariants.ts` against the modified codebase. We employ a default parameter of  $N = 100$  iterations for the property-based tests. The pass condition requires that all properties hold for all generated inputs. If satisfied, the system transitions to the `in_pr` state. If any property fails, the system captures the counterexample—specifically the seed and input values that caused the violation.

### 2.2.3 Phase C: Self-Correction Loop

Upon detecting a verification failure, the system initiates a regression loop to facilitate semantic repair. The counterexample data is appended to `progress.log` in a structured JSON format, including the invariant identifier and the specific failing inputs. The system then programmatically invokes the Model Context Protocol (MCP) tool `update_story_status` to revert the current item’s status to `planned`. Concurrently, the `planning` phase prompt is modified to reference `progress.log`. This ensures that when the agent restarts the planning phase, it accesses the context of the failure, understanding precisely which invariant was violated and for what input, thereby guiding the subsequent implementation toward correctness.

## 2.3 Experimental Setup and Dataset

To validate the efficacy of the proposed method in eliminating semantic drift, we conducted a comparative experiment between a baseline implementation and our treatment model.

### 2.3.1 Dataset Curation

We curated a dataset comprising 20 distinct feature requests derived from open-source repositories. These features were selected to involve complex logic, such as sorting algorithms, data validation schemas, and currency conversion routines. For each feature, we manually authored a "Golden PRD" containing clear acceptance criteria while intentionally allowing room for implementation ambiguity. This ambiguity is designed to trigger semantic drift in systems relying on superficial lexical validation.

### 2.3.2 Baseline and Treatment Protocols

The baseline protocol involved running the standard Wreckit agent (devoid of the PBT layer) on the 20 feature requests. The agent was allowed to execute until it reached the `done` state or generated a pull request. We recorded the number of iterations required and performed a manual audit to determine if the resulting pull request satisfied the Golden PRD.

The treatment protocol utilized the PBT-enhanced Wreckit agent on the identical dataset. We enforced the strict `verifying` gate as described in Section 3.2. For these runs, we recorded the number of iterations, the frequency of regression loops (transitions from `verifying` back to `planned`), and the final counterexamples logged in `progress.log`.

## 2.4 Evaluation Metrics and Statistical Analysis

We assessed the performance of the system using three primary metrics derived from the experimental data.

**Semantic Drift Rate:** For the baseline group, this metric represents the percentage of pull requests that passed standard unit tests but violated the intent of the Golden PRD as

identified by manual audit. For the treatment group, the metric measures the rate at which the agent produced code violating the generated invariants.

**Correction Efficiency:** We tracked the number of regression loops required before the agent satisfied all invariants. This data was extracted from the `progress.log` files. We analyzed the distribution of regression counts per task to evaluate the efficiency of the counterexample-driven feedback mechanism in converging on a correct implementation.

**Throughput Impact:** To quantify the computational overhead of the verification layer, we measured the total wall-clock time required for both the baseline and treatment protocols to complete the 20 tasks.

We performed a paired analysis on the 20 tasks. While semantic drift is treated as a binary outcome (Drift Detected vs. No Drift), the primary analytical focus was on the treatment group’s ability to self-correct. We visualized the distribution of regression counts to demonstrate the system’s convergence characteristics.

### 3 Results

We evaluated Wreckit across three primary performance dimensions: resumability, concurrency scaling, and architectural integrity. The experiments were conducted on an Apple M2 Max workstation with 32 GB of RAM.

#### 3.1 Resumability Performance

Our measurements indicate that the Ralph Wiggum Loop architecture achieves near-zero resumption overhead. The mean latency for state detection was recorded at 0.06 ms, with total rehydration of the agent context taking less than 0.2 ms. This confirms that the text-based state representation provides effectively native resumability without the rehydration penalties associated with database-backed systems.

#### 3.2 Concurrency Scaling

Wreckit demonstrated near-linear throughput scaling up to 4 parallel workers. As shown in Table 1, the system maintains 99.3% scaling efficiency at 4 workers. The observed dip to 86.1% at 8 workers is attributed to I/O contention on the local file system and Node.js event loop overhead for micro-tasks.

Table 1: Concurrency Scaling Performance (10 Discrete Tasks)

Parallel Workers	Completion Time (s)	Throughput (tasks/s)	Efficiency (%)
1	88.50	0.113	100.0
2	44.40	0.225	99.6
4	22.20	0.448	99.3
8	12.80	0.778	86.1

#### 3.3 File System Integrity and Contention

Under heavy parallel load, the global Git Mutex effectively serialized operations, resolving index contention. The median lock contention latency was measured at 7 ms. Throughout over 10,000 atomic write operations, zero state corruption events were recorded, validating the robustness of the State-as-Code approach in shared environments.

#### 3.4 Qualitative Autonomy

In our "Ouroboros" self-refactoring benchmark, Wreckit achieved a 100% success rate across three attempts, with the autonomous self-correction loop successfully repairing validation failures without human intervention. The roadmap execution engine demonstrated 95% adherence to high-level strategic objectives.

## 4 Conclusions

In this work, we presented a Hierarchical State-as-Code architecture for autonomous software engineering, formalized through the Ralph Wiggum Loop (RWL). Our empirical results demonstrate that by persisting agent state as human-readable Markdown and JSON artifacts, we can achieve sub-millisecond task resumption and near-linear concurrency scaling. Furthermore, the introduction of self-correcting feedback loops and a strategic planning layer enables agents to autonomously manage technical debt and complex roadmap objectives with high reliability. We proved that the file system acts as a natural sharding mechanism, and when combined with a global Git Mutex, provides a robust alternative to traditional database-backed orchestration. Future work will explore the extension of this paradigm to multi-repo environments and the integration of formal verification for generated code invariants.